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Optical component specifications

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Abstract

Three areas of optical component specifications are discussed in detail: (1) purely optical, (2) opto-mechanical, and (3) beauty or scattering specifications. Emphasis is placed on the level of tolerancing as it affects the function of the final optical system. Numerous graphs and tables are used to interpret the functional meaning of the specifications.

Introduction

The purpose of optical component specifications is to communicate the designer's idealizations to the fabricator. The specifications the designer puts on his design indicate the degree to which he will permit the realization to depart from his idealization.

While it is easy to say that specifications aid communication with the fabricator, there are some serious problems with writing specifications. First, the design is often less than perfect. Second, realization of the design cannot help but degrade the performance. Third, all parameters of the design including those involved in its realization affect performance. Therefore, the tolerances on those parameters affecting the design must be realistically balanced. This too is easy to say, but often the design tolerances are not analogous to measurable quantities, thus making it more difficult to arrive at a realistic tolerance budget. Also, there are parameters such as environmental conditions that will obviously affect performance, which the design program does not address.

Another problem is that for every specification called out, some parameter must be measured to show compliance, and this means additional cost. Similarly, too few specifications mean that you may not get the lens you desire, with the result that this too can be costly. Finally, while a designer starts with an idealization, the fabricator starts with a formless piece of glass. He works from something without shape, adding one surface at a time, each in proper relationship to one another. Toward the end of the cycle, often three or four dimensions must simultaneously be brought into tolerance.

Types of optical specifications

Within this framework of conflicting desires and realities, we must look at the various types of optical design specifications. First, there are the purely optical specifications, which are primarily materials related. These have to do with the absolute index, its variation about the nominal, and its variation with wavelength or dispersion. Then there are opto-mechanical considerations, such as figure, curvature, thickness, and centering. From there we go on to beauty and scattering specifications, which include bubbles, scratches, digs, bevels, and edge painting. Finally, there are coatings, which we will not discuss in this paper except to say that coatings are best specified in terms of what they ought to do rather than what they ought to be made of. The coater is in a much better position to determine the type of material to use to achieve the desired function.

Optical specifications

Optical specifications deal primarily with specifying glass type. The recommended way to specify glass is by an alphanumeric name, such as BK7 or SF4, and a type number, a six-digit number the first three digits of which are the index of refraction (n_d) minus one and the final three digits are the dispersion (v_d) with the decimal point coming before the last digit. Thus, as an example, BK7 is known as 517642 because $n_d = 1.517$ and $v_d = 64.2$. It is also wise to remember to specify only preferred glass types from the catalog whenever possible. The quality, price, and delivery will all be better than for non-preferred types.

Absolute index

Once a glass type is selected, we must specify its quality. Quality is determined by the index of refraction tolerance, the dispersion tolerance, the precision with which these data are measured, the striae grade, homogeneity, stress birefringence, and bubble quality. The availability of the various grades of glass according to the control of the absolute index of refraction and dispersion relative to catalog values are shown in Table 1. We

Table 1. Glass Grade according to Absolute Index and Dispersion Control Relative to Values Listed in the Glass Catalog.

		Absolute index of refraction	Dispersion (%)
Grade	Standard	±0.001*	±0.8**
	Grade 3	±0.0005	±0.5
	Grade 2	±0.0003	±0.3
	Grade 1	±0.0002	±0.2
Measurement	Standard	$\pm 3 \times 10^{-5}$	$\pm 2 \times 10^{-5}$
	Precision	$\pm 1 \times 10^{-5}$	$\pm 3 \times 10^{-6}$
	Extra precision	$\pm 5 \times 10^{-6}$	$\pm 2 \times 10^{-6}$

* Meets ¶3.3.4 of MIL-G-174A
** Meets ¶3.3.5 of MIL-G-174A

should note that the standard quality absolute index of refraction and dispersion as supplied by Schott Optical Glass Company meet the requirements of MIL-G-174A, ¶3.3.4 and 3.3.5.

Since the absolute index of refraction and dispersion are specified independently of the measurement accuracy, the designer is given considerable freedom to approach a design. In a prototype lens, the designer may not care exactly what index glass is used as long as he knows exactly what it is so that he may reoptimize the design. On the other hand, for a production run of several years, it may be better to specify Grade 2 glass and let the glass company supply the same index glass delivery after delivery.

Homogeneity and striae

In addition to absolute index of refraction there are specifications concerned with variations in index. There are two types of index variation: one, a long-range variation known as homogeneity, and the other a very localized phenomenon known as striae. Normal grade glass is examined for striae in one direction only and may have isolated fine striae. This is known as striae grade B per MIL-G-174A, ¶3.3.8.2. Precision striae quality is examined for the absence of any striae in two directions and is the commonly used grade for prisms. This is equivalent to striae grade A of MIL-G-174A, ¶3.3.8.1. For extremely exacting requirements a Schlieren or grade AA striae quality is available. Glass of this type has been examined in three orthogonal directions for the absence of striae.

The term homogeneity specifies large spatial scale variations in the index of refraction of the glass. There are five homogeneity grades as shown in Table 2. These grades are largely dependent on the form in which the glass is delivered. The higher homogeneity grades require considerable selection and testing on the part of the glass manufacturer and consequently premium prices. The normal homogeneity grade has a variation of $\pm 1 \times 10^{-4}$ within any one melt. There is no military specification on homogeneity. The requirement here is entirely design dependent and may be derived from figure requirements for a particular element. Field lenses will have lesser homogeneity requirements than objectives, for example, and larger objectives will require greater control over homogeneity.

Both homogeneity and stria variations in index are due to chemical variations within the melt. Once the glass has solidified, there is nothing the glass manufacturer can do to improve these variations. The material can only be graded and separated into various quality levels by sawing up the glass.

Table 2. Homogeneity Grade Classifications

Normal	$\pm 1 \times 10^{-4}$ within one melt
H1	$\pm 2 \times 10^{-5}$ within a selected melt
H2	$\pm 5 \times 10^{-6}$ within a cut blank
H3	$\pm 2 \times 10^{-6}$ within a cut blank
H4	$\pm 1 \times 10^{-6}$ depending on size and glass type

Stress birefringence

There is another type of variation that is physical in nature. This is stress induced birefringence caused by strain locked into the glass during cooling. The normal birefringence grade is 10 nm/cm or less retardation. This grade meets MIL-G-174A, ¶3.3.6.

The precision grade is obtained by a more stringent annealing cycle and produces 6 nm/cm or less retardation. Some glasses may be obtained with even less birefringence for a premium (see Table 3). The annealing process, in addition to reducing the stress-induced birefringence, slightly raises the absolute index of refraction. It is necessary therefore when keeping track of the index of a particular batch of glass to record both "melt numbers." The first melt number is truly a designation of the melt and thus the chemical nature of the glass. The second number is a record of the annealing process. Since not all glass from a particular melt undergoes similar annealing, both numbers are required for an unambiguous description of the glass. Melt data have been recorded by most manufacturers since the mid 1940's and may be obtained from the manufacturer measured to the quality level specified in the original order.

Table 3. Stress Birefringence Grades (Annealing Quality)

Normal*	≤ 10 nm/cm	up to 300 mm diameter
NSK (or precision)	≤ 6 nm/cm	
NSSK PSSK	≤ 3 to 4 nm/cm depending on glass size and type	

*Normal grade meets MIL-G-174A ¶3.3.6 for stress-induced birefringence

Bubble quality

The final material property to be concerned with is bubble quality. As can be seen from Figure 1, there are relatively few glass types in the lower quality bubble groups. The figure indicates the maximum number and size of bubbles per unit area to be found in each classification assuming glass elements with a 10:1 diameter-to-thickness ratio. Note that bubbles less than 0.06 mm are not counted.

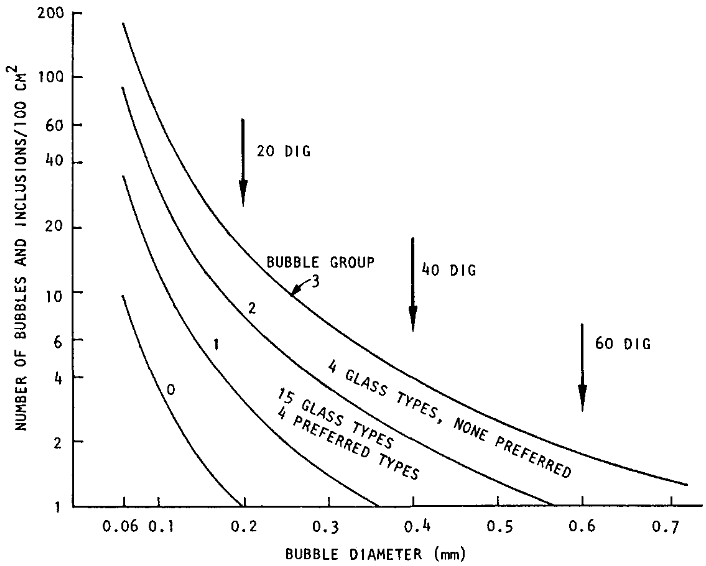


Figure 1. Number of bubbles vs bubble diameter for the Schott bubble groups.

Opto-mechanical specifications

Figure

The first opto-mechanical specification we should consider is that of figure, or the surface error on the optical element we are specifying. Surface error should always be specified in wavelengths of roughly 0.6 μm. This is the wavelength commonly used to measure departures from sphericity in most optical shops. To see the effect of a particular surface error on the wavefront, multiply the surface error by (n-1)/n to obtain the wavefront error produced by that one surface. To keep track of error buildup from multiple surfaces, it is common practice to take the root sum square of the surface errors to find the cumulative effect as is shown in Table 4. Caution is advised in the case of elements made individually, as it is possible to have a symmetric error buildup. The same type of radial error may occur on many surfaces within a lens where elements are made one at a time. Then the root sum square is not an accurate representation of the cumulative effect.

It should be pointed out that it is difficult to maintain good figure and high surface quality at the same time. The type of laps needed to obtain good figure somewhat degrade the surface quality of the elements. Also, note that the figure of cemented elements may be many times looser than the glass-air interfaces of the same elements. It is advisable, however, to hold a slightly convex test plate match between cemented surfaces. Figure 2 shows the required surface accuracy as a function of the number of surfaces to hold the transmitted wavefront to λ/4. While these results may seem surprisingly loose, Figure 3 adds a new dimension when glass homogeneity is taken into account. This figure shows the allowable surface error per element as a function of thickness to hold the transmitted wavefront of that element to λ/4 (or λ/8). Because homogeneity is a large spatial scale effect, this graph is probably conservative for small elements (say 2-in. diameter or less). It is probably a realistic representation for large elements and for pressings.

Table 4. Method of Finding the Root Sum Square Error of Random Contributions to Wavefront Error for a Single Element.

Wavefront error	Surface error 1	Surface error 2	Homogeneity	Birefringence

$$h = \sqrt{(h_1)^2 + (h_2)^2 + (h_3)^2 + (h_4)^2}$$

$$h = \sqrt{(n-1)^2\varepsilon_1{}^2 + (n-1)^2\varepsilon_2{}^2 + (t\Delta n)^2 + (t\delta)^2}$$

ε_1 = surface error on surface 1

ε_2 = surface error on surface 2

t = thickness

Δn = variation in index (homogeneity)

δ = stress birefringence (10 nm/cm = 1×10^{-6})

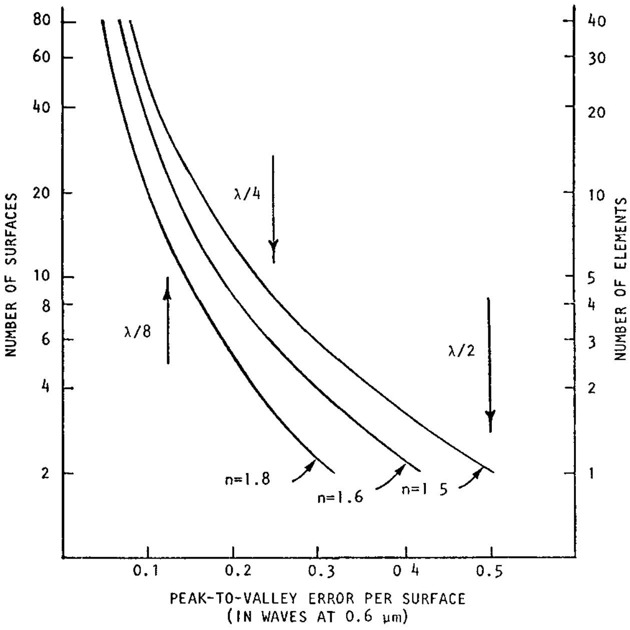


Figure 2. Surface error required for λ/4 transmitted wavefront assuming random error distribution.

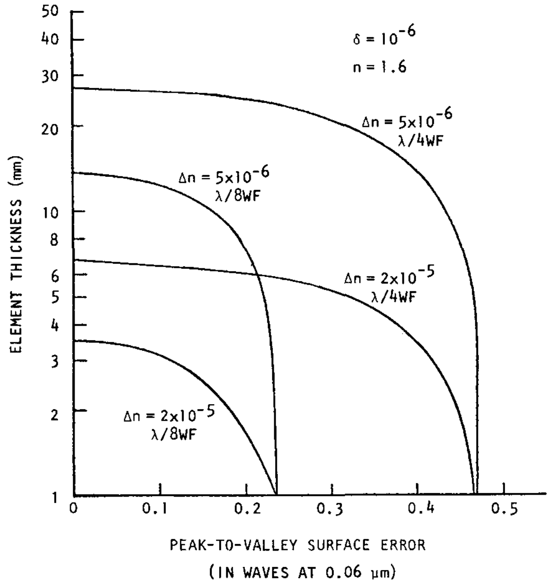


Figure 3. Maximum element thickness allowable to hold wavefront error to λ/4 (or λ/8) for several Δn.

Radius of curvature

For radius of curvature, always specify radius rather than curvature because radius is what the optician measures. In no case should the radius be specified tighter than $\lambda/4$ over the clear aperture. Anything tighter than this is difficult or impossible to measure. Furthermore, most optical parameters in a system are proportional to changes in curvature rather than radius. Thus in tolerancing radii, first tolerance all surfaces as a percentage of the curvature and then change this curvature tolerance into a radius tolerance. The same effect is gained by tolerancing $\Delta R/R^2$ as a constant percentage. This effect is illustrated in Figure 4 where we have shown the limiting radius tolerance, ΔR_t, as a function of element diameter and surface radius of curvature assuming ability to read a test plate match to $\pm\lambda/4$. For example, if a system of elements were all 40 mm in diameter, then a 40-mm radius surface can be controlled to ±0.0012 mm and a 400-mm radius surface to ±0.12 mm.

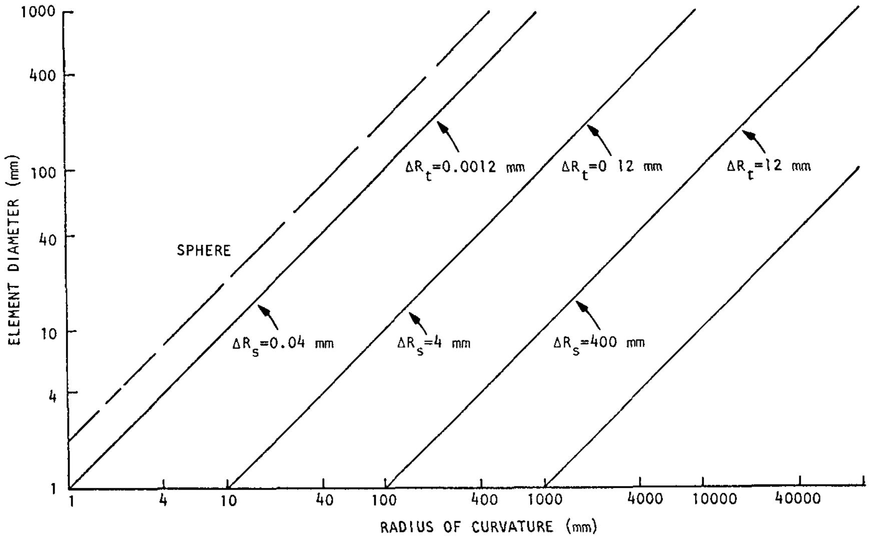


Figure 4. Limits on radius control assuming spherometer reading to 0.005 mm (ΔR_s) and test plate reading to $\lambda/4$ (ΔR_t).

Although it is common to see the radii on test plates toleranced, this is not good practice. The radius tolerance ought to be applied to the lens radii themselves rather than to the test plate. This is the only way to be consistent in tolerancing lens radii. Furthermore, if a radius is accurately known even though it is not precisely what is called for in a design, the design can be recomputed for the particular radius and the spacings of the lens elements can be reoptimized. Finally, as pointed out earlier, it is necessary to watch the radii on cemented surfaces. The reason for holding a slight convex match between the two elements is to prevent air bubbles from being trapped when the surfaces are cemented.

Center thickness

It is advisable to keep the center thickness tolerance as loose as possible. This is because the center thickness is a hazardous dimension to measure, and slip leaves a permanent mark in the center of the lens. The tighter the tolerance, the more often the dimension must be measured during fabrication. Also, the center thickness is the only variable the optician has to adjust for any mistakes in other dimensions or for beauty defects. A commonly used tolerance that is comfortable to work with is ±0.1 to ±0.05 mm. Do not be surprised if the lens elements, when delivered from the vendor, all tend to be at the high limit of the tolerance. In fact, if you find some lenses that appear to be toward the bottom side of the tolerance you can be sure that the vendor had trouble with that batch of lenses.

Centering

Perhaps the most confusing of the tolerances to apply correctly is that of centering.

This is because it is commonly thought that when centering is specified, two things are being specified at once. It is thought that the optical axis of the lens element is coincident with the mechanical axis. In fact, it takes two points to determine a straight line and centering specifies only one. Thus, centering per se removes only the wedge in the element or makes the mechanical axis cross the optical axis somewhere within the optic itself as shown in Figure 5. Although the element is free of wedge, the edge or periphery is not necessarily parallel to the optical axis, the axis joining the centers of curvature of the two surfaces.

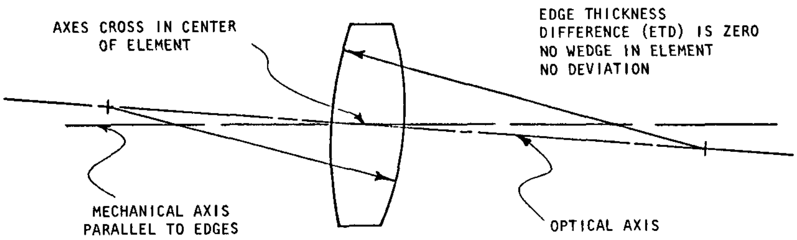


Figure 5. Diagram of centered lens.

When an element is free of wedge, its optical deviation $\alpha_0 = \alpha_m(n-1)$ is equal to zero where α_m is the mechanical wedge. This optical deviation is related to an easily measured quantity, the edge thickness difference (ETD) or wedge between the two surfaces as the lens is rotated, by the relationship

$$\text{ETD} = \frac{\alpha_0 D}{(n-1)} = \frac{D\Delta y}{(n-1)FL} ,$$

where D is the diameter of the lens, Δy is the decenter or distance between the optical and mechanical axes in the middle of the element, and FL is the focal length of the lens. An ETD of 0.005 mm is about the best that can be expected of high-quality production centering equipment. Using this as an upper limit, Figure 6 has been prepared to provide an estimate of optical deviation and decenter as a function of lens diameter and focal length. Notice that optical deviation depends on diameter but is independent of focal length while decenter depends on both quantities. An optical deviation α_0 of 3 minutes or less meets the requirements of MIL-O-13830A, ¶3.7.9.3 for centering.

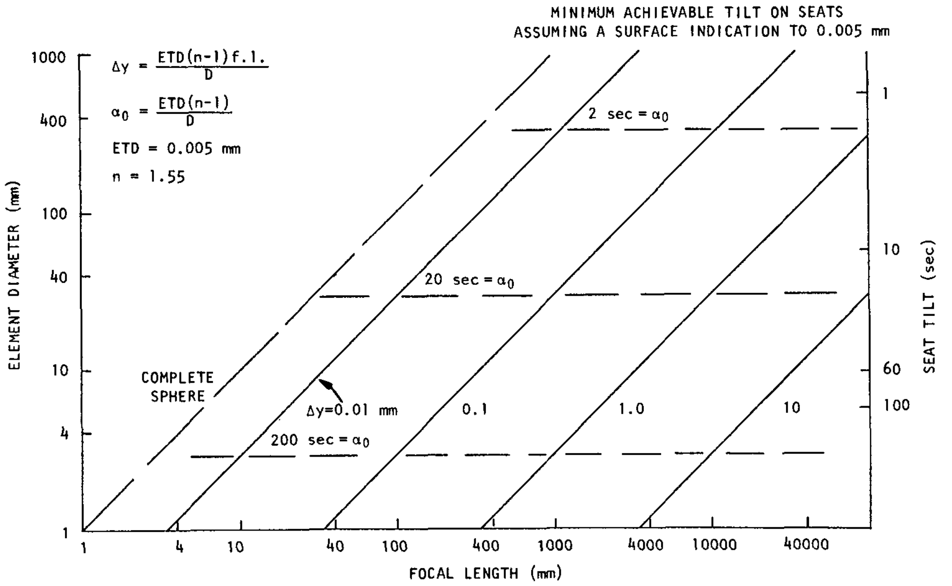


Figure 6. Limits on centering by controlling wedge or ETD.

To edge a lens so that it is centered as one would normally think of being truly centered, tilt as well as centering must be specified. Only in this way is it possible to be certain that the optical and mechanical axes will be coincident within the tolerances set.

In order to mechanically correct for tilt and centering one surface, usually that surface next to the chuck on the edging machine must be made to run true. Then the lens is slid on the chuck about the surface until the wedge or edge thickness difference is made to zero. This procedure is illustrated in Figure 7 showing the use of a dial indicator to test for running true.

Tilt correction needs to be specified whenever an element has a flat seat or when there is a particularly thick edge. Otherwise the element will not seat correctly in the cell. Be advised, however, that the tilt correction will probably not be made unless it is specifically called out on the optical drawing. Figure 8 shows an element that has been centered by edging and a seat ground during the same operation to be perpendicular to the optical axis. This element is free of tilt and decenter. It should be pointed out in passing that centering requirements for aspherics are more stringent than for spherical surfaces.

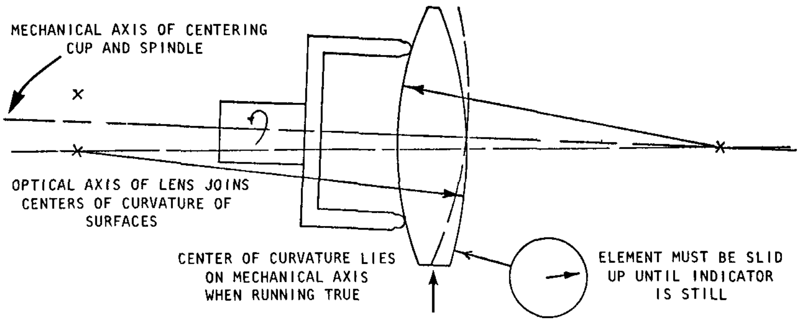


Figure 7. Procedure for centering a lens.

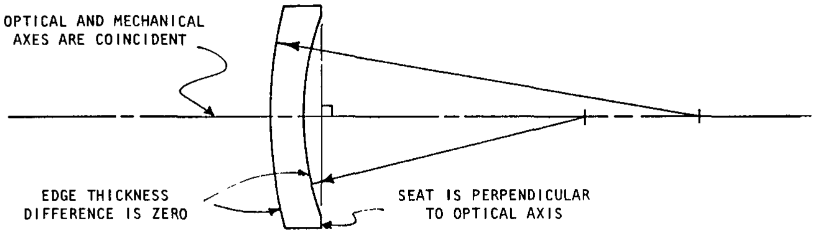


Figure 8. Diagram of centered lens also free of tilt.

Diameter

The diameter of a lens is intimately connected with the centering operation. It looks like a simple item to specify, yet many parameters influence the tolerance on this dimension. We should consider the cell design, the relative thermal expansion between the cell and the lens, edge blackening, centering per se, and the assembly method before assigning a tolerance to this dimension. The diameter tolerance does include a specification for roundness and taper. If either of these need to be held more tightly than the diameter tolerance band, they too must be called out separately, although this is very unlikely.

One final matter on diameter. For cemented elements, it makes the job of centering much easier for the optician during cementing if the diameters of the elements are held to one-half the decentering tolerance. If the diameters are tightly controlled, the optician can use a V-block jig to facilitate the centering while cementing.

Bevels

The last item of opto-mechanical specifications concerns bevels. Bevels are required by MIL-O-13830A to be 0.2 to 0.5 mm wide. Bevels should be considered a necessity on every optical element where there are right angle or acute edges. The bevel is necessary to protect the element both while it is at the vendor's shop and during assembly at the buyer's shop. Bevels smaller than 0.1 to 0.2 mm offer little protection while bevels larger than 0.5 mm usually require special tooling. Large bevels also tend to increase scattered light within the system and they use up clear aperture. Remember to always leave some room between the bevel and the clear aperture. The optician uses this space during centering and blocking as a non-critical area for holding the element and for indicating during centering.

Beauty Specifications

When we mention beauty specifications the first thing we normally think of are the scratch and dig specifications. These specifications were written basically as beauty standards, but in fact, upon careful examination, the writers of these specifications also had scattering in mind. A careful analysis of these specifications as outlined in Figure 9 and Table 5 will show that this is the case. Figure 9 is an attempt to interpret ¶3.5.2.1 and 3.5.2.1.1 of MIL-O-13830A. First, the length of all the 80 scratches is less than one quarter the diameter of the element, that is, 10 mm is less than 65/4 = 16.3 mm. Second, the sum of the combined scratch lengths times the corresponding scratch numbers (or scratch widths as given in Table 6) gives a figure less than half the maximum scratch number, taken as 80 for this example.

By applying the criteria of paragraph 3.5.2.1.1 and the apparent widths of the scratches, the results of Table 5 are obtained. In the table it is assumed that all of the light hitting the beauty defects is scattered and the scattering is computed on an area basis for a 100-mm diameter sample. The scattering due to digs appears much worse than the other beauty defects because one maximum size dig is permitted for every 20 mm of diameter and the dig sizes are large compared to the other defects. The saving feature is that digs are not too common a defect. It does suggest, however, that a designation of 80-10 or 60-10 might be better than 80-50 in many cases.

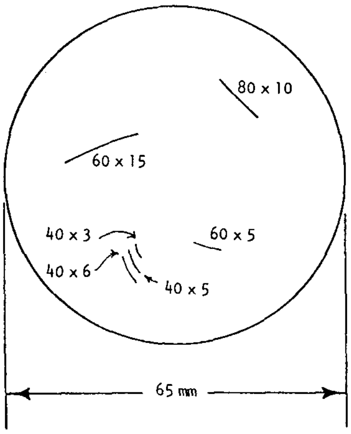


Figure 9. Interpretation of paragraphs 3.5.2.1 and 3.5.2.1.1 of MIL-O-13830A. Surface specified as 80-50.

80 x 10/65 = 12.3
60 x 15/65 = 13.8
60 x 5/65 = 4.6
40 x 14/65 = 8.6

39.3

Less than ½ of 80.
Lens meets specification.

Table 5. Theoretical Amount of Scattering due to Beauty Defects as Calculated on an Area Basis for a 100-mm Diameter Sample.

Designation	Group	Parts per million
Bubble	0	3
	1	10
	2	25
	3	50
Dig (per surface)	10	125
	20	500
	40	2000
	50	6400
Scratch (per surface)	10	6
	20	12
	40	25
	60	38
	80	50
	120	76

Table 6. MIL-STD Size Classification of Beauty Defects

MIL-O-13830A Transparent surfaces		MIL-C-48497(MU) Opaque surfaces	
Scratch No.	Width (µm)	Scratch letter	Width (µm)
80	8	G	120
60	6	F	80
40	4	E	60
20	2	D	40
10	1	C	20
		B	10
		A	5
Dig. No.	Diameter (µm)	Dig letter	Diameter (µm)
50	500	G	700
40	400	F	500
20	200	E	400
10	100	C	200
5	50	B	100
1	10	A	50

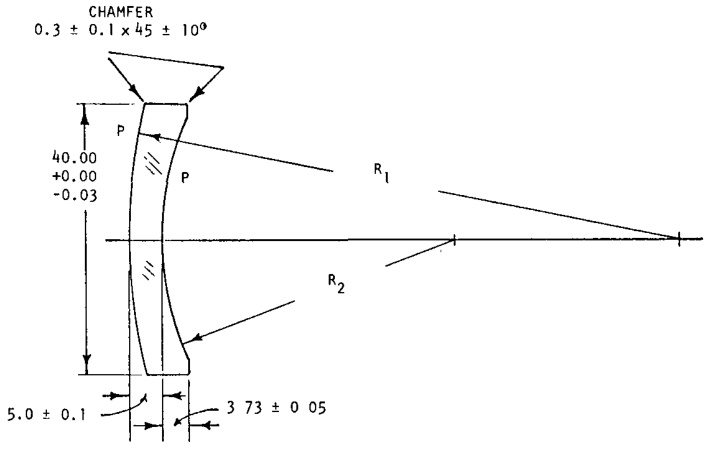
Note: per MIL-O-13830A, the scratch designation can be determined only by comparison with a set of standard scratches maintained by the Army. The width listed is the "apparent" width. MIL-C-48497(MU) is an actual measured width.

Whenever a beauty specification is called out it is necessary to clearly define the clear aperture on both sides of the element. Otherwise the optician has no way of knowing over what region of the lens the beauty specification applies. Remember too, that bubbles and inclusions within the glass are included in the beauty specification. On the other hand, coating defects are counted in addition to those specified on the drawing as surface defects.

There are two scratch and dig standards which apply to optics. MIL-O-13830A applies to refractive or transparent optics while MIL-C-48497(MU) applies to the coatings on reflective or opaque optics. MIL-O-13830A still applies to the substrate. Note that the definitions within these two specifications as outlined in Table 6 are substantially differen As a final comment on beauty specifications, wherever it is desirable to reduce scattered light and veiling glare, it is imperative that the edges and bevels of optical elements be blackened with edge coating to reduce scattering.

Conclusion

While it is regrettable that there is no overall standard that applies to specifications for optical elements, it is hoped that some of the material above will help in the understanding of what specifications are intended to do and how the optician or fabricator looks at these specifications. Figure 10 is an illustration of a typical element drawing, which is specified as best we can using the principles outlined in this paper.



	Radius	Figure	Clear aperture	Surface quality
R_1	80.22 ± 0.04	λ/4	37	60-40
R_2	43.44 ± 0.01	λ/4	33	60-40

Material: SF-4 755276

n_d, Grade 3; ν_d, Grade 3

Precision measurement

Striae Grade A, Bubble group 1

Homogeneity H2, Precision quality (PH2)

Notes:
(1) Surfaces marked P, polished. All others, fine ground.
(2) Blacken edge, seat, and bevels. No buildup allowed.
(3) Centering, ETD 0.02 mm
Seat ⊥ to axis to 0.02 mm.
(4) λ = 0.63 µm.

Figure 10. Lens element example. All dimensions in millimeters. Full scale.