Lens barrel optomechanical design principles

Mete Bayar
Pacific Optical
a Division of Recon/Optical, Inc.
2660 Columbia Street
Torrance, California 90503

Abstract. It is the task of an optomechanical engineer, starting with a lens design provided by the optical designer, to devise a structure which holds various components of a lens in proper axial and radial alignment. This structure, the lens barrel, must provide a means of interfacing with the customer's system, and must be designed so as to maintain optical and mechanical integrity under a multitude of environmental conditions. This discussion encompasses the design and analysis efforts undertaken by the optomechanical engineer to comply with this requirement.

Additionally, some special areas of concern to the optomechanical engineer such as various centration and assembly techniques, cementing of optical components, sealing and leak rate analyses, and reliability estimates of lens assemblies are discussed.

Keywords: optomechanical design; optical instrumentation; lens barrel design; materials.

Optical Engineering 20(2), 181-186 (March/April 1981).

CONTENTS

1. INTRODUCTION

Optomechanical engineers provide the crucial link between an optical design and deliverable hardware by using the basic principles of optical and mechanical engineering.

There is an ever-increasing demand for diffraction-limited or nearly-diffraction-limited lenses as the systems in which these lenses are used become more complex and sophisticated. These lenses are expected to maintain an extremely high level of performance under a multitude of environmental conditions. Therefore, the problem is not only to optically design these lenses, but to mount them such that the level of excellence designed into the lens is maintained in operation.[1-8]

The lens barrel, defined by MIL-STD-1241A[9] as the "mechanical structure holding a complete lens," is used to position elements axially and radially with respect to each other, and to provide a means of interfacing the lens assembly with the system.

Special considerations given to barrel design are in the areas of material selection, element mounting, and lens assembly techniques. Special areas of concern are glass-to-glass and glass-to-metal cementing, purging and sealing, and the reliability estimates for lens assemblies.

2. BARREL MATERIAL SELECTION

The first step in designing the optimum barrel is the selection of the appropriate barrel material. To achieve this, both operating and nonoperating temperatures must be considered. During the design phase, the optical designer works with the mechanical engineer and makes every effort to minimize the thermal rate coefficient (or thermal coefficient of defocus) of the lens assembly for a given barrel material by judicious selection of glass types. Then it becomes the task of the mechanical engineer to design the barrel which maintains the optical integrity under the operating environment, and the mechanical integrity under the nonoperating environment. To achieve this goal, an environmental analysis is conducted to consider the thermal as well as shock and vibration levels to which the lens assembly will be subjected, sometimes with contradictory conclusions.

To minimize the axial and radial stresses which disturb the surface accuracy and cause image degrading strains on elements during thermal extremes, a minimum of force must be applied. However, to retain the elements in proper axial and radial alignment under shock and vibration, it may be necessary to apply large forces. Further, under nonoperating conditions, applied stresses must never exceed the ultimate strength of glass, which would cause a fracture. Careful selection of barrel material will greatly help alleviate these problems.

In addition to thermal and rigidity considerations, the mechanical designer must consider weight, cost, and manufacturability tradeoffs.

Four different metals are predominantly used in fabrication of lens barrels. These are aluminum, stainless steel, beryllium, and titanium. Nonmetallic materials, such as carbon fiber composites, which have excellent weight-to-strength characteristics, are not considered here, even though these materials may find extensive use in the future, especially for long focal length aerial reconnaissance lenses. The pertinent characteristics of the metals used in lens barrels and some common glasses are listed in Table I.

2.1. Aluminum

Aluminum is light (.097 lb/in^3) and possesses excellent machining characteristics. The most commonly used aluminum alloys for lens barrels are 6061-T6 and 2024-T4. The major shortcoming of aluminum is its large coefficient of expansion, 13.3×10^{-6} in/in°F in comparison to glass, with a coefficient of expansion of approximately 4×10^{-6} in/in°F. This difference may cause image degradation and may even result in breakage if the thermal requirements are stringent. But because of its low cost, easy machinability, and high

---

Invited paper OM-105 received Sep. 26, 1980; revised manuscript received and accepted for publication Oct. 29, 1980. This paper is a revision of Paper 193-11 which was presented at the SPIE seminar on Optical Systems Engineering, Aug. 27-28, 1979, San Diego. The paper presented there appears (unrefereed) in SPIE Proceedings Vol. 193.

TABLE I. Comparison of Barrel Materials and Typical Optical Glasses

Metal/Glass	Density (lb/in^3)	Coefficient of Expansion (10^{-6} in/in°F)	Modulus of Elasticity (10^6 lb/in^2)	Thermal Conductivity BTU/ft-hr-°F
Aluminum	0.097	13.3	10	128
Stainless steel				
Austenitic (316)	0.29	8.9	28	9.4
Martensitic (416)	0.28	5.5	29	14.4
Beryllium	0.067	6.4	40	92
Titanium				
Ti-6A1-4V	0.164	4.9	16	10.1
BK-7	0.090	3.94	11.8	—
SK-16	0.129	3.5	12.9	—
SF-5	0.147	4.5	8.15	—
PSK-53	0.129	5.2	11.16	—
KzFS-1	0.124	2.78	8.0	—

conductivity which allows it to achieve thermal equilibrium quickly, aluminum is extensively used in the optical field.

2.2 Stainless steel

The austenitic (300 series) or martensitic-ferritic (400 series) stainless steels are extensively used as barrel materials when the thermal requirements are stringent. As the table indicates, the coefficient of expansion of 416 stainless steel is 5.5×10^{-6} in/in° F, which closely matches that of the glass. An additional advantage to stainless steel is its excellent corrosion resistance characteristics.

The stainless steels, however, are difficult to machine and are heavy. The density of stainless steels is .28 lb/in^3 which makes them approximately three times heavier than aluminum. Another iron-base material used in lens barrels is Invar which is an iron/nickel alloy containing 36 percent nickel. This material possesses a very low coefficient of expansion, $.70 \times 10^{-6}$ in/in° F, but is costly, heavy, and difficult to machine. Super Invar has an even lower coefficient of expansion, $.60 \times 10^{-6}$ in/in° F, but has the same disadvantages as the Invar.

2.3. Beryllium

Beryllium with very low density (.067 lb/in^3), high stiffness, and an acceptably low coefficient of expansion (6.4×10^{-6} in/in°F) would seem to be an excellent barrel material. Its high cost and machining difficulty, however, make this metal undesirable. Machining beryllium is hazardous to the operator unless highly efficient exhaust systems are used to maintain the beryllium dust concentration below acceptable limits.

2.4. Titanium

Titanium alloys, particularly the Ti-6Al-4V, are excellent barrel materials. Titanium has a coefficient of expansion very close to glass, 4.9×10^{-6} in/in° F, and its density is fairly low, .164 lb/in^3. Titanium is stable and yields itself to grinding and lapping operations, even though some work hardening is encountered. The shortcomings of titanium are high cost and difficult machinability. A further disadvantage is its low thermal conductivity, which keeps the metal from reaching thermal equilibrium quickly.

3. ELEMENT MOUNTING TECHNIQUES

Elements of a multielement lens must be mounted so that the centers of curvature of all the surfaces fall on a common line called the optical axis. Additionally, elements must be positioned with respect to each other so that the airspaces specified by the optical designer are achieved. It is the mechanical engineer's task to design a lens barrel to fulfill these two conditions.

The barrel design effort of the mechanical engineer is normally preceded by a tolerance analysis by the optical designer to determine the sensitivity of various elements to variations in airspaces, center thicknesses, radii of curvature, and decentration. These tolerances must be properly allotted by the mechanical designer during the barrel design.

3.1. Radial constraints

Three mounting arrangements are used at Pacific Optical to constrain elements radially. These methods are hard mounting, drop-in mounting, and elastomeric mounting.

Hard mounting. In this type of mounting, elements are radially positioned by the inside diameter (ID) of the barrel wall. The outside diameter (OD) of the elements must be ground, and the ID of the barrel must be machined such that the element axis cannot be displaced beyond an acceptable tolerance. In a high acuity lens, clearance between the OD of the element and ID of the barrel may vary at room temperature from less than 0 to .0004 inch depending on the sensitivity of the element.

A thermal stress analysis must be conducted to determine the levels of compressive stresses to which the elements will be subjected during the temperature extremes. To achieve this, equations developed for "hoop stresses" can be used. Equations shown in Fig. 1 give the compressive stresses on glass and metal parts as a function of temperature differential, coefficient of expansion, modulus of elasticity, element radius, and barrel wall thickness. Glass possesses a high compressive strength (greater than 50,000 lb/in^2), and fracture almost always occurs in tension since the tensile strength of glass is less than its compressive strength by an order of magnitude.

$$S_g = \frac{(\alpha_M - \alpha_g)\,\Delta T}{\left[\frac{1}{Eg} + \frac{r}{E_M X t}\right]} \text{ lb/in}^2 \quad \text{RADIAL. STRESSES ON GLASS}$$

$$S_M = S_g \frac{r}{t} \text{ lb/in}^2 \quad \text{RADIAL STRESSES ON METAL}$$

α_M = METAL COEFFICIENT OF EXPANSION
α_g = GLASS COEFFICIENT OF EXPANSION
ΔT = TEMPERATURE DIFFERENTIAL
E_g = MODULUS OF ELASTICITY - GLASS
E_M = MODULUS OF ELASTICITY - METAL
r = RADIUS OF ELEMENT
t = THICKNESS OF BARREL

Fig. 1. Radial stresses—glass and metal.

Of primary concern during the operating thermal extremes is the strain caused by compressive stresses which result in birefringence and the consequent image degradation. Ideally, the stresses should be below 500 lb/in^2 for the operating temperature range to minimize strain and the associated birefringence.

In the hard-mount method of element mounting, the axial positioning of elements is accomplished by cutting the seats during assembly. The obvious advantage of hard mounting is that once positioned, the elements remain in their desired position within the required tolerances under shock and vibration.

The disadvantages are the extremely close machining tolerances required on the barrel ID and the equally stringent edging tolerances on the glass OD. The lens barrel must often be heated to create sufficient clearance to install the elements during assembly.

The cross section of a hard-mounted version of a high performance 24-inch fl, f/3.5 aerial reconnaissance lens is given in Fig. 2. The barrel material for this lens is titanium (Ti-6Al-4V).

Drop-in mounting. Another mounting method extensively used by Pacific Optical in mounting small lenses is the drop-in assembly. This assembly is similar to hard mounting in that the elements are radially constrained by the cell walls. The seats, however, instead o

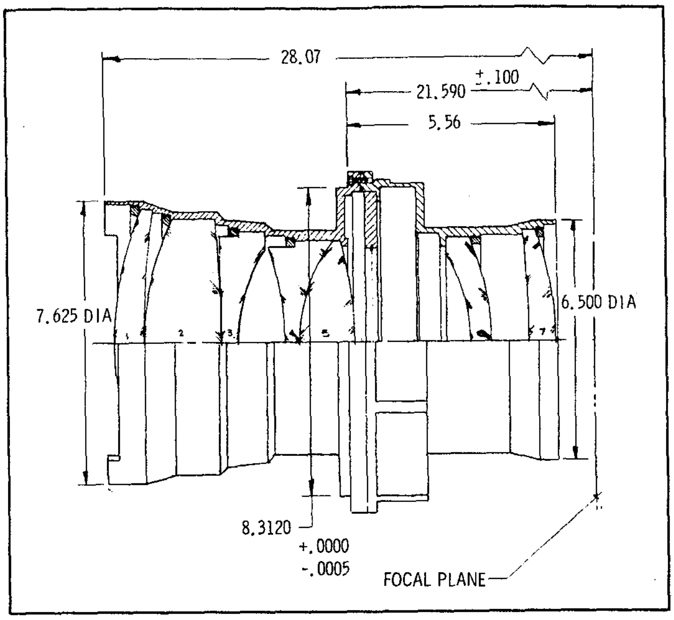


Fig. 2. 24-inch fl, f/3.5 lens.

being cut in assembly, are premachined within the prescribed tolerances. Figure 3 shows the cross section of a 3.05-inch fl, f/4, 4× computer output microfilming (COM) lens employing the drop-in mounting technique. This technique is excellent for small lenses not requiring extreme accuracy, even though it has also been successfully used with high acuity lenses by making tolerances sufficiently tight.

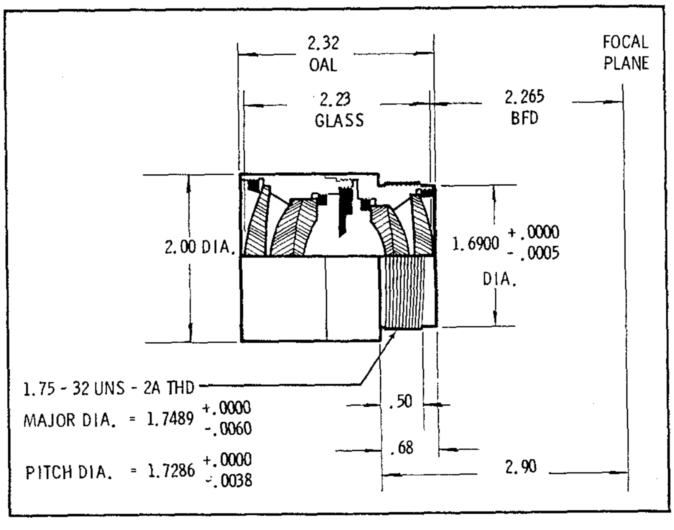


Fig. 3. 3.05-inch fl, f/4.4× COM lens.

Elastomeric mounting. The method most commonly employed by Pacific Optical to radially constrain elements is the elastomeric mounting technique. In this method, sufficient clearances are provided between the OD of the element and ID of the lens barrel so that the element can be adjusted radially in its seat until it is centered with respect to a reference piloting shoulder on the lens barrel. The lens barrel is mounted on a rotary table, an example of which is shown in Fig. 4, and the piloting shoulder of the lens barrel is first adjusted until it is concentric with the axis of rotation of the rotary table. To center the elements, both optical and mechanical measuring techniques are employed. An autocollimator or an interferometer is used to optically center the elements.

An autocollimator is schematically illustrated in Fig. 5, and an interferometer is schematically illustrated in Fig. 6.

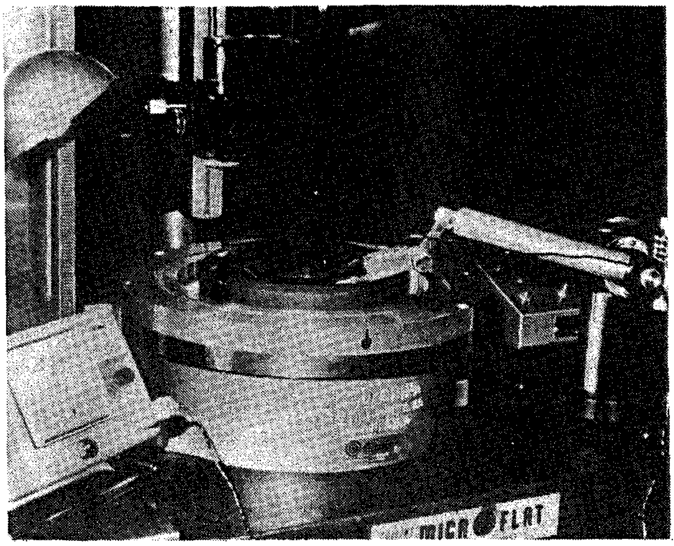


Fig. 4. Elastomeric mounting technique.

In the mechanical centering technique, a Federal Electronic gauge, which is capable of measuring edge runouts to within 5 μinches, is used to align the top surface of the element. After the element is centered within the required tolerances, the gap between the element OD and the barrel ID is filled with an elastomeric room temperature vulcanizing (RTV) compound encapsulating the edge of the element. The element is then axially retained by means of a retaining ring.

To obtain the optimum mounting, the thickness of RTV around the periphery of the element compensates for the differential expansion between the glass and the metal. A near-diffraction-limited 66-inch fl, f/8 objective lens using the elastomeric mounting technique is shown in Fig. 7.

Figure 8 gives the equation used to determine the optimum RTV thickness for thermal compensation. This equation gives the RTV thickness as a function of element diameter, and coefficients of expansion of glass, metal, and rubber. If the coefficient of expansion of the barrel material closely matches that of the glass, the RTV thickness is minimized and based strictly on assembly considerations.

The primary advantages of the elastomeric mounting technique are: strain-free mounting of large elements; accurate element alignment during assembly; and relatively loose element edging and metal bore tolerances.

The disadvantages are: the particular RTV compound used in the lens must be carefully selected to eliminate outgassing; and disassembly is difficult if it becomes necessary to make minor airspace adjustments to optimize performance.

3.2. Axial constraints

Three techniques are employed by Pacific Optical in axially constraining lens elements to maintain centration after alignment, and to maintain proper airspaces prescribed by the optical designer. These techniques are employment of retaining rings, snap rings, and spun rims to constrain elements against their respective seats as illustrated in Fig. 9. In high performance lenses, the threaded retaining rings are the most frequently employed means of constraining lens elements. Consequently, this discussion will primarily deal with retaining rings and the interaction of retaining rings with various seat configurations.

The retaining rings load the elements against seats which may be cut square, tangent to the radius of curvature of the element, or with the same radius of curvature as the element. The retainers themselves may also be square, tangent, or ground with a radius. These configurations are illustrated in Fig. 10. The square seats are the most commonly used seats and are the easiest to machine. However, when it is necessary to minimize the axial stresses, seats machined tangent to the element or having the same radius of

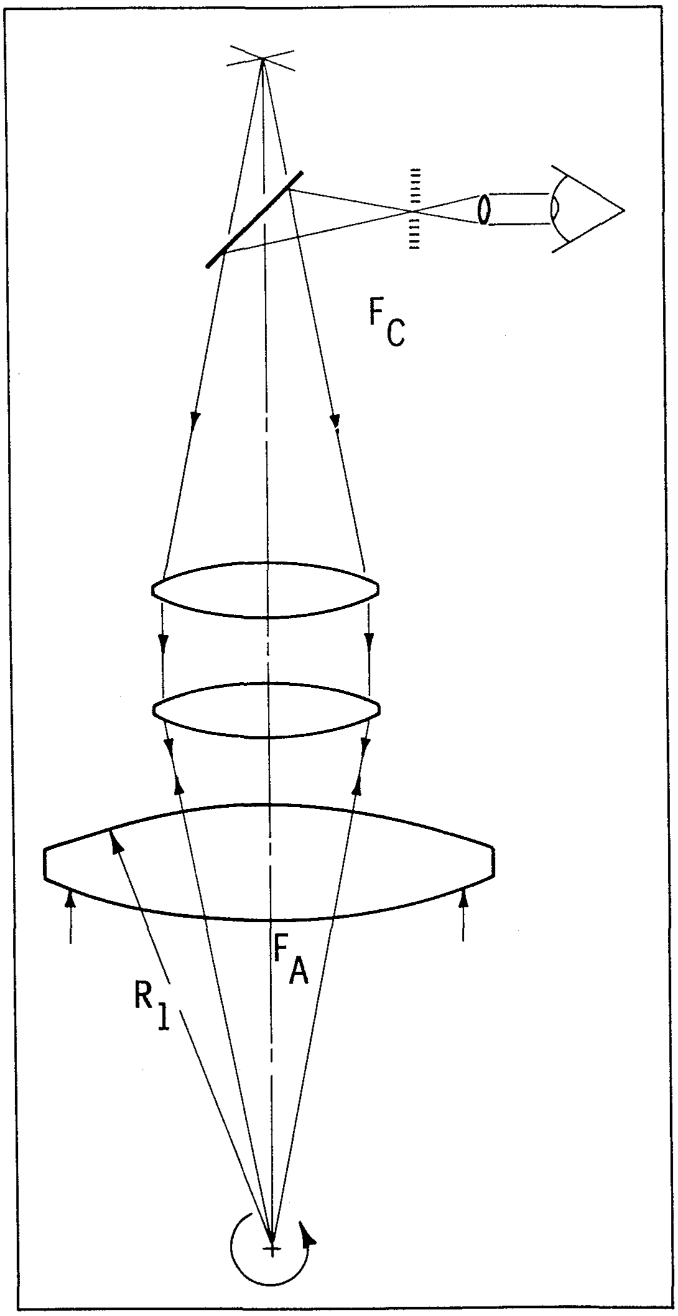


Fig. 5. Autocollimation method of checking center of curvature alignment.

curvature as the element are used.

Regardless of the seat configuration, whenever feasible, the element should be mounted against an active spherical surface. If the seat is accurately machined with respect to a given axis, the center of curvature of the active surface which rests on this seat will lie on that given axis. This surface may be rotated about its center of curvature to bring into alignment the center of curvature of the opposite surface. After this is accomplished, the element can be axially retained by the retaining ring. The retaining rings should be designed with loose fitting threads to minimize the possibility of decentering when they are tightened against the element. A stationary ring may be used on steep surfaces under the threaded retaining ring to minimize the possibility of decentering while tightening the retainer.

In a multielement design, elements rest on steps whose heights are carefully controlled to obtain the required airspaces. The height of a step between two elements may be calculated to obtain a given airspace by using the simple sag equations given in Fig. 11. In stack mounting, elements seat on spacers rather than the steps machined into the barrel. The spacer height, however, is calculated in the same manner.

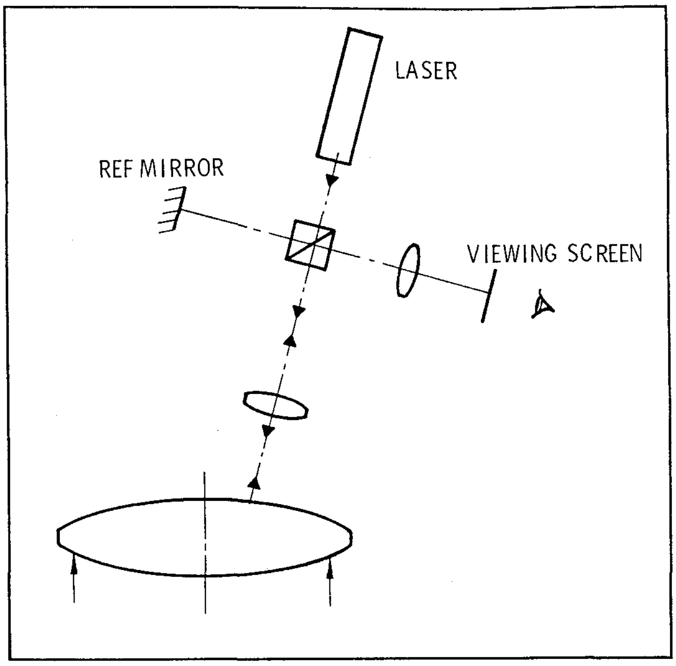


Fig. 6. Interferometer method of checking center of curvature alignment.

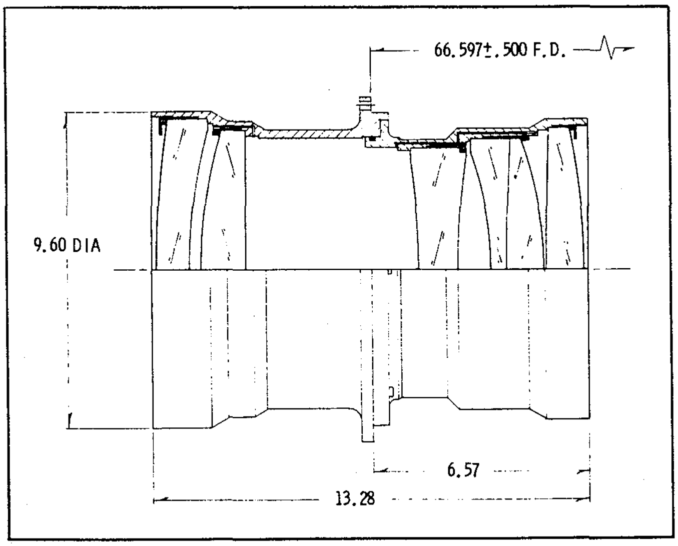
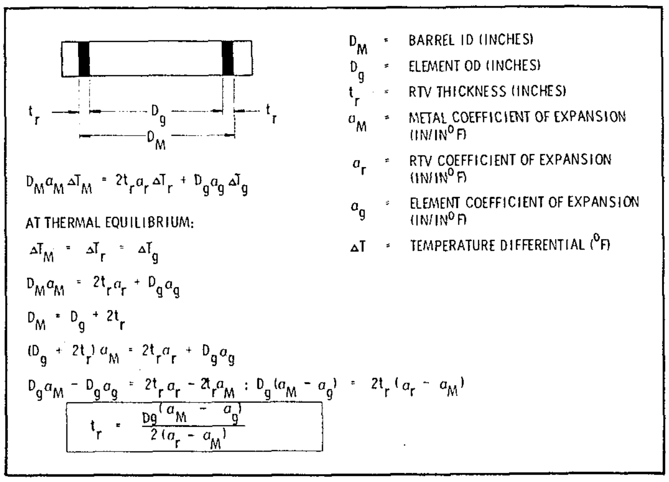


Fig. 7. 66-inch fl, f/8 objective lens.

To select the optimum seat configuration, the axial compressive stresses for a given temperature differential must be calculated for glass to ensure that these stresses are within the acceptable limits. Axial compressive stresses may be calculated using the equation given in Fig. 12. This equation gives the axial stresses as a function of glass and metal expansion coefficients, glass and metal modulus of elasticity, and temperature differential. The combined axial and radial stresses may be determined by taking the square root of the sum of the squares of axial and radial stresses.

Special precautions must be taken to assure that the line of contact of the seat is as directly opposite the line of contact of the retaining rings as possible to minimize bending moments. The tensile stress which results from the bending moments may be approximately calculated using the flat plate equation for edge-supported plates with uniform load on the concentric circular ring. This equa-



$$D_M \alpha_M \Delta T_M = 2t_r \alpha_r \Delta T_r + D_g \alpha_g \Delta T_g$$

AT THERMAL EQUILIBRIUM:

$$\Delta T_M = \Delta T_r = \Delta T_g$$

$$D_M \alpha_M = 2t_r \alpha_r + D_g \alpha_g$$

$$D_M = D_g + 2t_r$$

$$(D_g + 2t_r)\alpha_M = 2t_r \alpha_r + D_g \alpha_g$$

$$D_g \alpha_M - D_g \alpha_g = 2t_r \alpha_r - 2t_r \alpha_M : D_g(\alpha_M - \alpha_g) = 2t_r(\alpha_r - \alpha_M)$$

$$\boxed{t_r = \frac{D_g(\alpha_M - \alpha_g)}{2(\alpha_r - \alpha_M)}}$$

D_M = BARREL ID (INCHES)
D_g = ELEMENT OD (INCHES)
t_r = RTV THICKNESS (INCHES)
α_M = METAL COEFFICIENT OF EXPANSION (IN/IN°F)
α_r = RTV COEFFICIENT OF EXPANSION (IN/IN°F)
α_g = ELEMENT COEFFICIENT OF EXPANSION (IN/IN°F)
ΔT = TEMPERATURE DIFFERENTIAL (°F)

Fig. 8. Optimum RTV thickness.

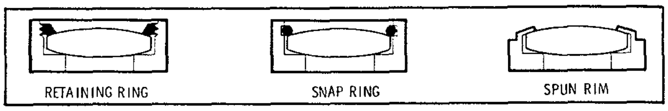


Fig. 9. Axial constraints.

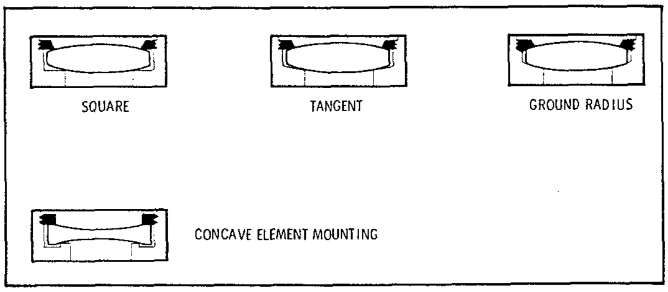
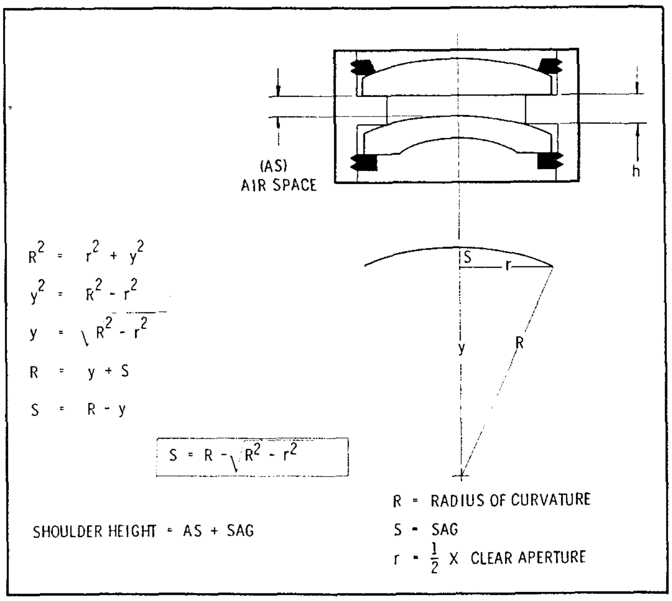


Fig. 10. Seat and retaining ring configurations.



$$R^2 = r^2 + y^2$$

$$y^2 = R^2 - r^2$$

$$y = \sqrt{R^2 - r^2}$$

$$R = y + S$$

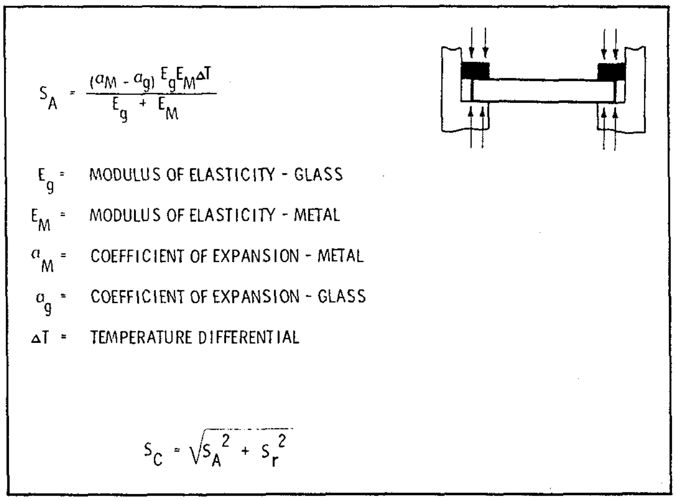
$$S = R - y$$

$$\boxed{S = R - \sqrt{R^2 - r^2}}$$

SHOULDER HEIGHT = AS + SAG

R = RADIUS OF CURVATURE
S - SAG
r - $\frac{1}{2}$ X CLEAR APERTURE

Fig. 11. Axial element positioning.

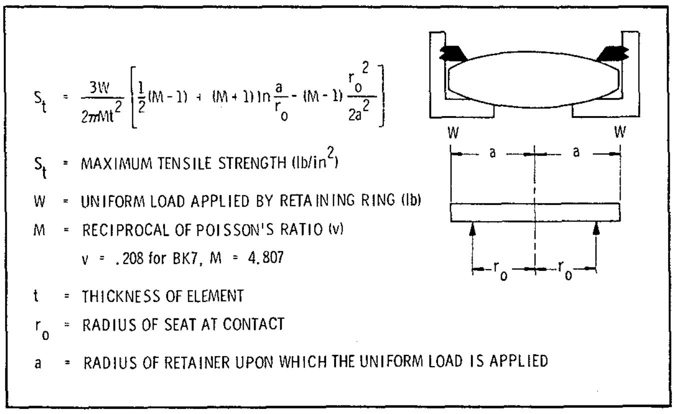


$$S_A = \frac{(\alpha_M - \alpha_g)E_g E_M \Delta T}{E_g + E_M}$$

E_g = MODULUS OF ELASTICITY - GLASS
E_M = MODULUS OF ELASTICITY - METAL
α_M = COEFFICIENT OF EXPANSION - METAL
α_g = COEFFICIENT OF EXPANSION - GLASS
ΔT = TEMPERATURE DIFFERENTIAL

$$S_C = \sqrt{S_A^2 + S_r^2}$$

Fig. 12. Axial and combined axial-radial stresses.



$$S_t = \frac{3W}{2\pi M t^2}\left[\frac{1}{2}(M-1) + (M+1)\ln\frac{a}{r_o} - (M-1)\frac{r_o^2}{2a^2}\right]$$

S_t = MAXIMUM TENSILE STRENGTH (lb/in^2)
W = UNIFORM LOAD APPLIED BY RETAINING RING (lb)
M = RECIPROCAL OF POISSON'S RATIO (v)
v = .208 for BK7, M = 4.807
t = THICKNESS OF ELEMENT
r_o = RADIUS OF SEAT AT CONTACT
a = RADIUS OF RETAINER UPON WHICH THE UNIFORM LOAD IS APPLIED

Fig. 13. Bending stresses.

tion is given in Fig. 13.

In high performance lenses, it may become necessary to lap the seat to minimize the possibility of an element resting on only the high spots which tends to bend the element with a consequent loss in surface accuracy. In addition to lapping the seats, the retaining rings may have to be slotted to increase their compliance to assure uniform pressure.

The tightening torque applied to the retaining ring must also be minimized while keeping it compatible with the shock and vibration requirements.

Interferograms, given in Fig. 14, dramatically illustrate what can happen to a surface figure if the retaining ring is not properly designed. Figure 14(a) shows an element resting on its lapped seat without a retaining ring. Figure 14(b) shows a solid retaining ring tightened with a light torque. Figure 14(c) shows the same retaining ring with moderate torque. Figure 14(d) shows a redesigned compliant retaining ring with moderate torque.

4. SPECIAL OPTOMECHANICAL TASKS

4.1. Cementing

Cemented doublets are extensively used in lens assemblies. The types of thermosetting cements to be used in the bonding of glass assemblies are defined in MIL-A-3920C.[10] Table II lists the cements and manufacturers approved by Frankford Arsenal as meeting the requirements of this specification.

If the lens thermal requirements are on the order of −80°F to +203°F, and if the elements are large and made of extraordinary glasses such as PSK and KzFS with large differences in coefficients of expansion, problems become severe and each cement must be carefully evaluated. Fairly good results may be obtained by using epoxy cements. The only way of assuring that the cemented doublet will meet the environmental requirements is to test it. The results will vary depending on the type, size, and shape of the elements.

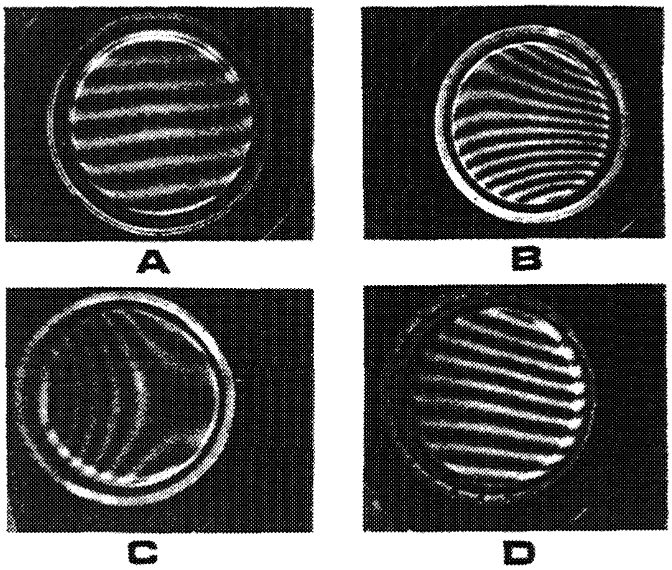


Fig. 14. Axial constraints—surface accuracy.

TABLE II. Adhesives—Optical Thermosetting

Manufacturer's Designation	Test or Qualification Reference	Manufacturer's Name and Address
HE-80	C3920C77	Eastman Kodak Company 20 Avenue E Rochester, NY 14251
NO A-61	B3920A76	Norland Products, Inc. 695 Joyce Kilmer Avenue New Brunswick, NJ 08902
F-65	A3920A77	Summers Laboratories, Inc. Fort Washington, PA 19034
UV-74	A3920A77	Summers Laboratories, Inc. Fort Washington, PA 19034
C-59	A3920A75	Summers Laboratories, Inc. Fort Washington, PA 19034
M-62	A3920A75	Summers Laboratories, Inc. Fort Washington, PA 19034

Glass-to-metal cements are used, in particular, to mount mirrors and prisms to metal components for system interface. The most extensively used glass-to-metal adhesives are Armstrong A-12, per MIS-23543B,[11] MIL Bond per MIL-A-48611,[12] manufactured by Summers Laboratories, Inc., and the adhesive per MIL-B-60621A,[13] manufactured by Narmco Materials, Inc. When the thermal environmental requirements are extreme, the metal component should be stainless steel, in particular 416 series, for coefficient of expansion matching.

4.2. Lens sealing—leak rate analysis

No special sealing or humidity control is needed for commercial lenses operating in a controlled environment. However, special precautions must be taken with lenses used in military applications to prevent fogging of the lens elements. Two methods are normally employed: lenses are either filled with dry nitrogen and sealed, or are vented through a desiccator. With the sealed lenses, the inside pressures vary from atmospheric to several lb/in^2 above atmospheric. In either case, passages must be provided between airspaces to assure complete purging between the elements. First and last elements are sealed with "O" rings or an RTV compound around the periphery of the element. If the barrel uses two or more cells, the interfaces between the cells must be sealed with face or plug "O" ring seals. The plug seals are normally preferred as they allow airspace adjustment between cells. A leak rate analysis must be conducted based on the permeability of seal materials to assure that some positive pressure will remain inside the lens between the specified maintenance cycles. The leak rate may be determined using the equation in Fig. 15. The leak rate for lenses designed for military applications are in the order of 1×10^{-6} cm^3/s to 2×10^{-6} cm^3/s. If a casting is used for the barrel, its porosity must be controlled. The casting must be impregnated and checked per MIL-STD-276[14] and MIL-I-6869.[15]

$$Q = K_p \times \frac{\pi D h}{w} \times P$$

Q = LEAKAGE RATE (cc/hr)

K_p = PERMEABILITY = $.73 \times 10^{-3} \frac{\text{cc in}}{\text{hr in}^2\text{atm}}$ FOR NITRILE

w = WIDTH OF THE COMPRESSED "O" RING

h = HEIGHT OF THE COMPRESSED "O" RING

D = MEAN DIAMETER OF "O" RING

P = PRESSURE DIFFERENTIAL (atm)

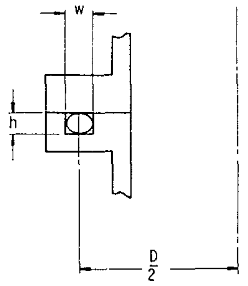


Fig. 15. Leak rate analysis.

5. CONCLUSIONS

It should be reemphasized that the barrel materials and mounting configuration for elements must be carefully considered by the opto-mechanical engineer during the mechanical design phase. Otherwise, the most sophisticated optical design will give completely unsatisfactory results in operation. Design of the optimum lens barrel is much more than just providing a holder for the lens elements.

6. REFERENCES

1. Daric, D. S. L., Machine Design, 184-190 (May 23, 1968).
2. Deterding, L. G., Appl. Opt. 1(4) 403-406(1962).
3. Koch, D. G., Comparison of Electronic and Optical Packaging Requirements, Nepcon Proceedings, Feb. 9, 10, 11, 1971.
4. Roark, R. J., *Formulas for Stress and Strain*, McGraw-Hill, New York (1975).
5. Scott, R. M., Appl. Opt. 1(4) 387-397(1962).
6. Smith, W. J., *Modern Optical Engineering*, pp. 427-431, McGraw-Hill, New York (1966).
7. Spotts, M. F., *Design of Machine Elements*, Prentice-Hall, Inc., Englewood Cliffs, N.J. (1958).
8. Yoder, P. R. Jr., Machine Design, 190-196 (May 23, 1968).
9. MIL-STD-1241A—*Optical Terms and Definitions*, March 31, 1967.
10. MIL-A-3920C—*Adhesive, Optical, Thermosetting*, February 21, 1977.
11. MIS-23543B—*Missile Specification—Bonding of Optical Assemblies*, April 5, 1979.
12. MIL-A-48611—*Adhesive System, Epoxy-Elastomeric, for Glass to Metal*, April 6, 1977.
13. MIL-B-60621A—*Bonding Optical Assemblies (Glass to Metal)*, November 20, 1969.
14. MIL-STD-276—*Impregnation of Porous Nonferrous Metal Castings*, February 2, 1956.
15. MIL-I-6869—*Impregnants for Aluminum Alloy and Magnesium Alloy Castings*, January 14, 1971.