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# Optical design for manufacture

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## ABSTRACT

Many factors beyond the optimization of radii, thicknesses, and glasses are critical to the optical system design task if a practical system is to be produced. We review the common factors and some that may not have been so obvious. We relate some specific examples from our experience. The designer is encouraged to keep various factors in mind when designing for manufacture with the aim of making cost effective designs.

## 1. INTRODUCTION

Our intent in this paper is to review some key points that optical designers should keep in mind when designing a system to be manufactured. We share some of our experiences in things that we have encountered or done ourselves that were not as good as they might have been. Most of these points are kept in mind by the experienced designer, but some may not yet have occured to the new designer in the field. We start our discussion with single surface factors and progress through components, doublets, component mounting, assembly, and alignment. Our company's principal business is in this area, so we have the opportunity to see these things on a daily basis. During the preparation of this paper, the supervisors in the optics fabrication and assembly areas were consulted for their examples and opinions. Some of the material is also drawn from our earlier efforts to determine practical tolerances for optical components where similar workers in the field were polled for their opinions and experiences(1).

## 2. SURFACE MANUFACTURE

The basic requirements for optical surface manufacture are radius, surface figure (irregularity of test glass interference fringes), and the functional or "beauty" defects of scratch, dig, and stain. In a given design, the radius tolerances can be assigned to insure that the system performance requirements are met on an absolute basis or with some high probability and/or on an economical basis as described in some of our earlier works(2,3). The tolerance on a radius can be stated in terms of the percentage of the radius, which we find most reasonable for design, but it is usually put on a drawing as a dimensional tolerance. The surface figure tolerance is usually expressed as allowable fringes of irregularity from a perfect sphere. In today's shop practice the radius can be measured accurately by a Zygo interferometer or equal with an appropriate linear scale. The fringe irregularity can be seen with all of the radius error effects removed by carefully setting the reference radius or by an automatic calculation in software. Therefore, if one were specifying a surface on the assumption of using an interferometer, the radius with a tolerance and the maximum irregularity is all that need be specified. However, if classical test glasses are used, they need to be within the radius tolerance and the part measured must be within some number of fringes of power to the test glass. If there are too many fringes difference in power, it is difficult to judge the irregularity superimposed on the rings. A four to one ratio of power to irregularity is reasonable.

Over the years, we have encountered, more than once, conflicting or unrealistic specifications of radius, power, and irregularity on "production" component drawings. One example was an "engineer" who wanted a 100" radius +-.005". Figure 1 shows the relative cost of manufacture versus radius tolerance where 0.13% was judged to be the limit at which a fabricator should accept a fixed price order to produce the surface. Tighter tolerances should only be accepted on a "time and material" basis in the typical shop environment. The "engineer" was asking for 0.005%. When confronted with the implication, he decided that +-1" would suffice! In another case, a government drawing had no specified tolerances on radii but had the power and irregularity when tested with specific Test Glass Numbers of the agency. These were neither provided nor defined as to actual radii! We often see a radius tolerance of some tight percentage and a power allowance which would allow the actual radius of a part which fit the test plate to be outside the stated tolerance. In this case, the surface should be made to the required power and irregularity on a test glass that meets the radius tolerance. One can ignore the fact that a best fit sphere on an interferometer seems to be out of the radius tolerance. The designer should have considered the effect of the combined radius tolerance and fringes of power in his tolerance budget (and he may have).

We have encountered a problem where the tolerances on the surface irregularity of an objective lens were about half as stringent as would be required to statistically expect to meet the system resolution, wavefront, or MTF requirements. This was particularly annoying to discover after all of a production lot of components reached the assembly stage. Another factor to keep in mind is that the effect on the transmitted wavefront of an irregularity as measured by a test glass or interferometer is proportional to the index minus one (N-1). For crown glass this might be about 0.52, but for germanium it is about 3.0 or six times as much. A mirror in air is 2.0 or four times as much. Beware also of the fact that a test glass whose diameter is half the clear aperture of the surface to be tested must see no more than about one quarter (1/4) of the irregularity allowed in the clear aperture. Subdiameter testing can be misleading if not properly analyzed.

It is our practice (and probably others) to optimize a system design with any reasonable radii to which the process leads. We then go to the list of available test glasses and tools to find those nearest the optimized radii. We evaluate the system as it would be using only existing test glasses and trying the nearest neighboring test glass radii substitutions to find the best combination. Occasionally it may be necessary to plan on making an additional new test glass to meet the requirements. If this is the case, then the design is optimized using the available test glasses and varying the new radius freely. Glass thicknesses and airspaces may be adjusted to better accomodate the available test glasses. The system sensitivity to small variations is then found and used to distribute the parameter tolerances either by using judgement based on experience or some of the more rigorous but time consuming methods previously described(1,2,3). The data is then ready for the preparation of drawings from which the components can be fabricated and the mountings designed and fabricated.

The reasonable distribution of irregularity allowances throughout the system might be approached with the concepts described by Smith(4) where the square root of the sum of the squares of the errors expected is set to meet the system wavefront requirements. Any deviation of the wavefront over the aperture of the wave forming the image is equally serious and independant of where it occurs in the optical train. However, the aperture of the beam may vary considerably at different surfaces of the system as shown in Figure 2. At the limiting aperture of the system, the wavefront fills the entire clear aperture and therefore the allowable irregularity per surface is that irregularity per the diameter of the clear aperture of that surface. However, nearer to the focal plane of that beam or wavefront, the wave may have an aperture much smaller than the clear aperture of that surface which is required for the various other angles that pass through the system. Here, a quarter fringe required over a 1/4" beam on a 2" clear aperture part might lead to a two fringe irregularity call out over the clear aperture. A reticle at the focal plane of the wavefront has virtually no concern for irregularity. In this case, some tolerance such as 4 or 8 fringe irregularity might be chosen just because further relaxation would not make the part significantly easier to produce or test. The cost versus surface irregularity is shown in Figure 3. The ability to hold a tight irregularity specification is influenced in a major way by the stiffness of the part or generally the ratio of the diameter to the thickness. This influence is shown in Figure 4 where beyond a 10:1 ratio is seen to be a big problem but 4:1 is little problem.

The converse of the irregularity distribution in the system applies to "beauty" defects such as scratches, digs, and stains. A scratch or dig near the limiting aperture or entrance pupil of a system tends to have no significant effect on the observed image. A defect near the focus such as on a reticle, however, will be obvious and probably annoying and possibly detrimental to the application. Figure 5 shows the relative cost to minimize such defects. It is important for the practical designer to keep in mind the frequently heard comment that practical "optics are made to look through, not at". These defects are of decreasing importance as the surface is further from a focal plane. In the case of high laser power through a system, defects can take on greater importance due to their propensity for laser damage, but even here, the distance from a focal plane reduces the vulnerability. Our assembly department also admonishes us to try to keep very steep curves away from focal planes if possible because it is very difficult to see defects on such surfaces until they are assembled and examined in an optical system.

Stain-prone and soft glasses cause some problems in practical manufacture. The neophyte designer may tend to ignore the glass stain numbers in his choice of glasses and tend to end up with the glasses that we like to say "dissolve in air." Something like SK16 or 620-602 for example causes us trouble with milky stains in the normal precision shop environment. We find we must coat these within one or two days after polishing or they have to be repolished. Figure 6 shows the relative cost of working various stain classes of glass. This implies that anything worse than 4 should be avoided if at all possible because the production cost is not very controllable. The infamous "TOW Reticle" of the Bradley Fighting Vehicle has caused many vendors problems because it is made of a soft glass and is at a reticle plane which must have an etched grove filled with a hard titania compound. There is a great tendancy for this surface to end up scratched and scrapped. It is not clear that an exotic or difficult glass has any good reason for appearing at a focal plane.

## 3. COMPONENT MANUFACTURE

The key additional requirement of component manufacture is the geometrical relationship of one surface of the component to another. The usual warning is to avoid thin edges on positive lenses and thin centers on negative lenses. The thin edges cause breakage problems in handling, mounting, and usage. Thin centers cause difficulty in maintaining surface figure. This is probably due to thermal gradients and flexure while polishing. The 10:1 rule above might be a bit severe for centers and edges, but it is a good place to start. Our shop asks that we keep bevels to .020" minimum and preferably .040+". This avoids chipping and somewhat helps reduce scratching. Smith(5) recently elaborated on how to design to avoid the manufacturing problem of centering a nearly concentric meniscus lens so that it can meet its wedge requirements. Figure 7 illustrates the problem. Very flat lenses can also be a centering problem because of similar geometrical problems.

Where practical, mirrors for production in any quantity can benefit by being designed to have all (or most) of the non-reflecting surfaces left as molded. This eliminates the cost of processing the backs and edges of the mirrors. The other extreme of edging cost is where we have a requirement to maintain a .0005" diameter tolerance on lenses where the edges must be painted. We have to edge, paint, and then edge the paint to meet this requirement.

## 4. DOUBLET ASSEMBLY

The requirement of doublet assembly is to maintain the geometrical relationship of one lens to the other. The cemented surface in a doublet is generally much less sensitive to surface irregularities and radius errors because there is little index change at the interface. A relaxed radius and power tolerance is usually practical because the major effect of the buried surface is on color correction. However, care must be taken in the manufacturing drawings to require that the surfaces to be cemented match to within about 5 fringes for good cementing. When two lenses are to be cemented to give beam deviations of less than about 2 arcminutes, making one of the elements about .020" smaller diameter is advisable. The one lens can then be centered optically with respect to the other without mechanical constraint rather than relying on tight centering and diameter tolerances on both components.

## 5. COMPONENT MOUNTING AND ASSEMBLY

The major requirement of component mounting is to position and hold a geometric relationship of the component to a mechanical reference position and orientation. Assembly must then position the mounted components correctly with respect to each other. Yoder(6) has an extensive discussion of these subjects in his book, which we believe should be in every designer's library.

Figure 8 shows an actual example of a problematic design where the lens indicated tended to fracture under thermal cycling. There are two problems with the design and specifications. The spacer ring exerts its force concentration too close to the edge of the lens which ends up chipping under the stress concentration. After some analysis, it was found that the most extreme rays came no closer to the ring than indicated on the drawing. The ring could therefore have had a considerably smaller inside diameter and alleviated the problem. This is the easiest fix after the lenses have been fabricated. A better redesign would be to make all of the lenses the same diameter to even simplify the machining of the main housing. The second problem with the specification was that a torque of 30 inch-pounds was implied on the retainer ring that compresses the O-ring. A more realistic torque where the O-ring is compressed to its design limit turns out to be 10 inch-pounds. Making this lens assembly to its original specifications and meeting all of the requirements is virtually impossible.

Many optical systems require bonding and/or sealing for proper execution. Those who design the mountings for optics should be intimately familiar with the properties of bonding and sealing compounds. A great deal of difficulty in optical instrument manufacture results from bonding problems. Some materials can both bond and seal, but not all materials do both well. Here we refer to bonding as a process which holds a part in a mechanical position so that it stays in that position to within the necessary tolerances. Sealing is generally used to retain a clean and dry atmosphere inside an instrument and keep out moisture, dust, etc. A usual problem is to hold a component in the proper relationship to its mount while a bonding agent is applied and solidified. The challenge of the designer is to have bonds which hold the parts rigidly enough for performance but flexibly enough to perform over wide ranges of temperature, shock, and vibration. Yoder(6) covers this subject in Chapter 6 of his text. The major problems that arise are that the bonds may not set to a stable equilibrium position, but drift in position with time and/or as further environmental stresses are experienced. Elevated temperature cure cycles are often required. This can necessitate careful fixturing where differential thermal expansion is taken into account. Figure 9 shows a technique which we used successfully to hold a prism in its mount during high temperature curing. The temporary holding screws had a polymeric core of high thermal coefficient of expansion whose length was designed to just compensate the differential expansion of the glass prism and its metal housing. Prior to this, we had a problem due to the housing and all-metal screws expanding more than the glass at elevated temperature thereby becoming loose. This allowed the bond to move before it cured.

Our assembly department prefers designs where mechanical retainers are used rather than bonding. This usually allows easy, fast, and reversable assembly. If a component needs to be removed for any of a variety of possible reasons, debonding may be difficult, hazardous to the component or operator, or just impossible. If a seal is required, they prefer to have the components mechanically fixed and then apply sealant after all is proven to be otherwise satisfactory. This is not to preclude the use of bonding if the life cycle cost tradeoff has been considered and favors it.

A common problem for assemblers is a lens which is nearly, but not quite, symmetric so that it is difficult to see if it is being assembled in the right orientation. If a design comes out with a lens of this type, it is often worthwhile to try to find an adjusted solution with the same radius on both sides. The lens cannot then be assembled in the wrong orientation and one less test glass and set of radius tools will be required for manufacture of the lens.

We have encountered a challenging problem with a mirror on an axel which uses the mirror as part of its structure as shown in Figure 10. Any misalignment of the shafts or their corresponding bearings (and other sources) can cause forces perpendicular to the axes of the axel shafts which then act on the mirror itself. This can warp the mirror and cause astigmatism in the wavefront reflected from the mirror. A mirror is more sensitive to warping than a lens because of the N-1 effect mentioned above and also because of another factor. A window or lens which is the ideal shape before mounting but becomes warped in mounting has only a small effect on the transmitted wavefront. If part of the front side of the lens is warped in a given direction, the back side follows it and the optical thickness does not change. Any warping of a mirror perpendicular to its surface, however, will change the wavefront by twice that amount. The desirable practice is to design mirror mountings to avoid transmitting stress from the mounts to the mirror substrate. This has been the classical mounting problem of astronomical mirrors since the time of Newton.

Black oxide coated ferrous metals such as the 400 series stainless steels cause significant problems when used in cells and mountings. The black oxide parts have very limited corrosion protection and a soot-like dust rubs off of the surfaces. When a stack of lenses and spacers are placed in a cell there is a tendancy to get this dust on the lenses. When the threaded retainer is installed against the stack, an additional cleaning step may be necessary. The assembler's work area tends to resemble a "coal mine" which is not conducive to clean optical assemblies. It is difficult to keep parts corrosion free through the steps of handling, storage, and cleaning. Even more challenging is the task of achieving `water break free' surfaces for bonding without inducing corrosion. A major problem is the common use of 17-4PH alloy castings. The extreme care that must be exercised during processing these parts to avoid corrosion is more costly than one might realize. If these metals must be used, we prefer a black chrome finish which has none of the problems mentioned. The higher initial cost of black chrome versus black oxide coating is definitely offset during subsequent processes. It has become apparent from changes to drawing packages that we have seen in the past few years that a severe "field problem" with corrosion exists on black oxided ferrous metal parts used externally. We hope that the internal parts will get the same attention due to the severity of the problems just discussed.

## 6. ALIGNMENT

Alignment is usually required to make small final adjustments to the positions and orientations of some of the components so that the total assembly meets the performance requirements such as focus, resolution, field of view, direction of view, field orientation (plumb or tilt), etc. We will not belabor the problem of systems designed with too many or too few adjustments since we discussed it at length in our first paper on tolerancing(2). Having too few adjustments and the attendant need for tight component tolerances leads to expensive components. Too many adjustments add complexity and cost to the system and tend to lead the alignment technician in wasteful circles. This latter problem can be overcome by proper alignment procedures which fix the unneeded adjustments to some nominal values and use the rest for alignment. However, it is not cost effective to make an adjustment which will not be used.

One fact that a new system designer may not realize until it causes him a problem is that a 1:1 magnification lens system as seen in Figure 11 cannot be focused in the usual sense by moving the lens group. If the lens is moved one unit away from the object and toward the image plane, the image moves one unit toward the lens. The only solutions are to change the distance between the object and image planes to match the lens or change the lens to match the object to image distance. In a symmetric 1:1 relay, it may be practical to change a central airspace where the light is collimated.

The author had occasion to design for production a system which used two different 1:1 relays in series to relay an erect image. Since there was no system requirement on image quality at the intermediate focus, the system parameters were left free to try to correct aberrations between the two relays with the smallest number of elements. The resulting design formed a good image at the required focal plane but not at the intermediate focus. Subsequent experience has led to speculation as to whether the life cycle cost might have been reduced by adding another element to each relay so that each would form a good image by itself. This would allow the performance of each relay to be checked more easily in production. Null lenses were designed and built, after the fact, so that the individual relays could be checked independently when a problem arose. It is not clear at this point as to which is most cost effective in this case: a test lens which stays in the shop but is harder to use, or a "built in test" lens in each relay.

We have had experience with a folded relay system that brought to our attention a problem that we had not previously considered. It is common to think of aligning a system so that the images are properly positioned. However, if there are folding reflections, it may also be critically important to align the pupils in the system. There are essentially two somewhat independent paths that must be simultaneously in alignment: the images and the pupils. In an unfolded system, the pupil path is often sufficiently aligned without even thinking about it. However, we have learned not to take that for granted in systems of any complexity.

## 7. SUMMARY

We have discussed some of the principles of optical design for manufacturability and shared some of our experiences (not all of which were good, but all of which were valuable to us). We think the most valuable designers are those who keep the whole picture in mind from design through manufacture to end use and maintenance. Some extra effort on the part of the designers can often save thousands of times that effort in the life of a product.

## 8. ACKNOWLEDGEMENTS

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## 9. REFERENCES

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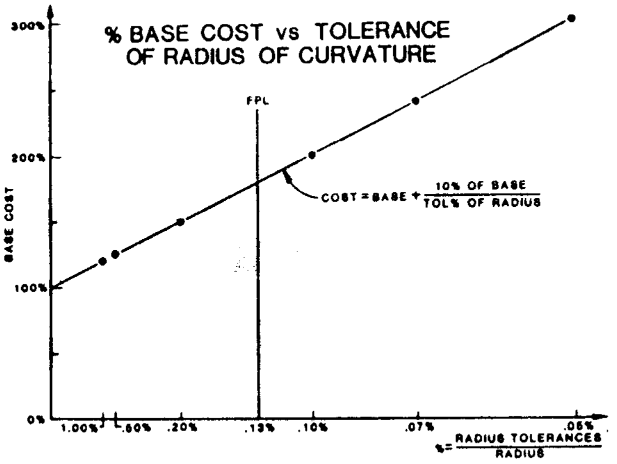

Fig.1 Percentage of base cost versus radius tolerance plotted on a reciprocal scale.

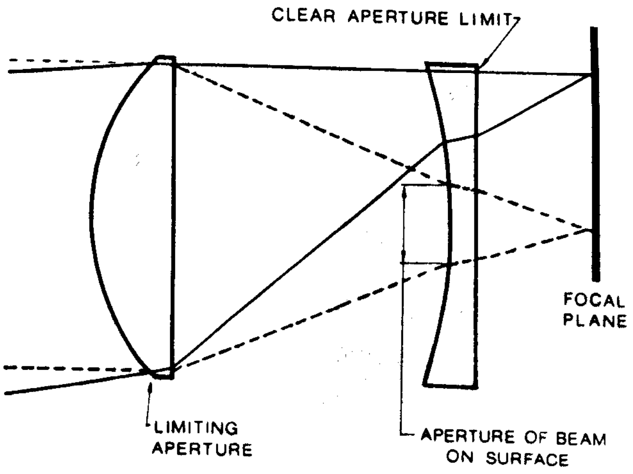

Fig. 2. Variation of diameter of wavefront to clear aperture with position along the optical path.

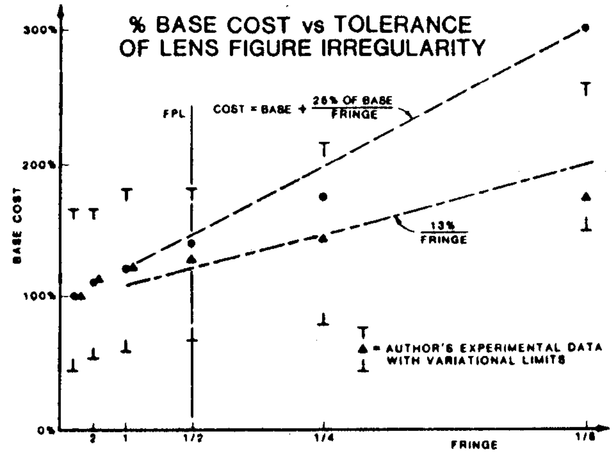

Fig. 3. Percentage of base cost versus surface figure irregularity plotted on a reciprocal scale.

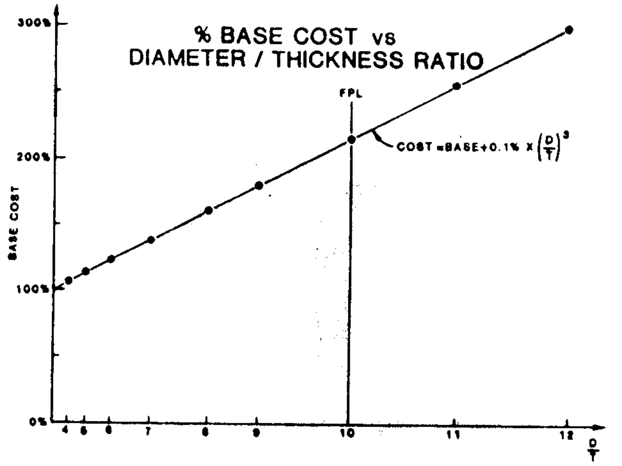

Fig. 4. Percentage of base cost versus the diameter to thickness ratio of a glass window, mirror, or lens.

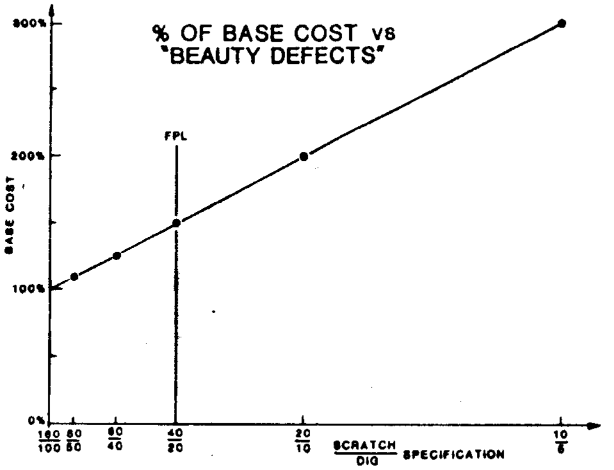

Fig. 5. Percentage of base cost versus surface finish, scratch and dig, or "Beauty" defect specifications.

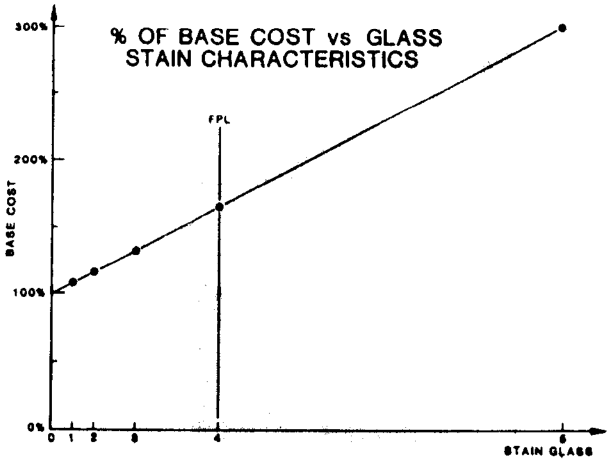

Fig. 6. Percentage of base cost vs. glass stain characteristics.

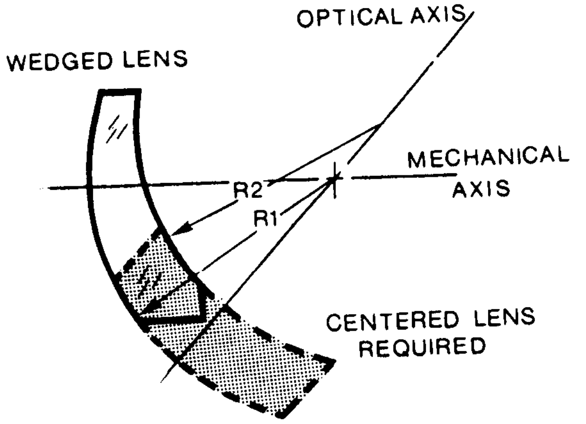

Fig. 7. A wedged element whose surface centers are near the same position may not be centerable because optical axis and mechanical axis are skewed at too great an angle (after Smith(5)).

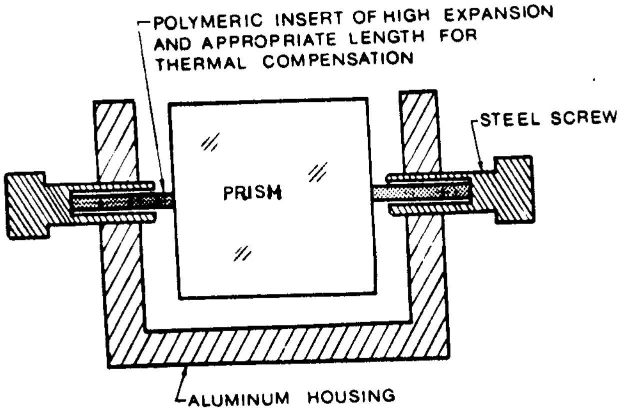

Fig. 9. Thermally compensated screws for holding prism in position in housing during high temperature bonding cure cycle.

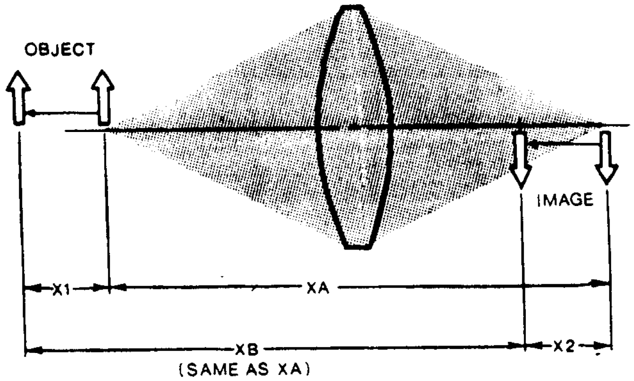

Fig. 11. Focus problem of a 1:1 relay lens. XA equals XB because X1 equals X2 at 1:1 magnification, therefore it cannot be focused by moving the lens toward or away from the focal plane.

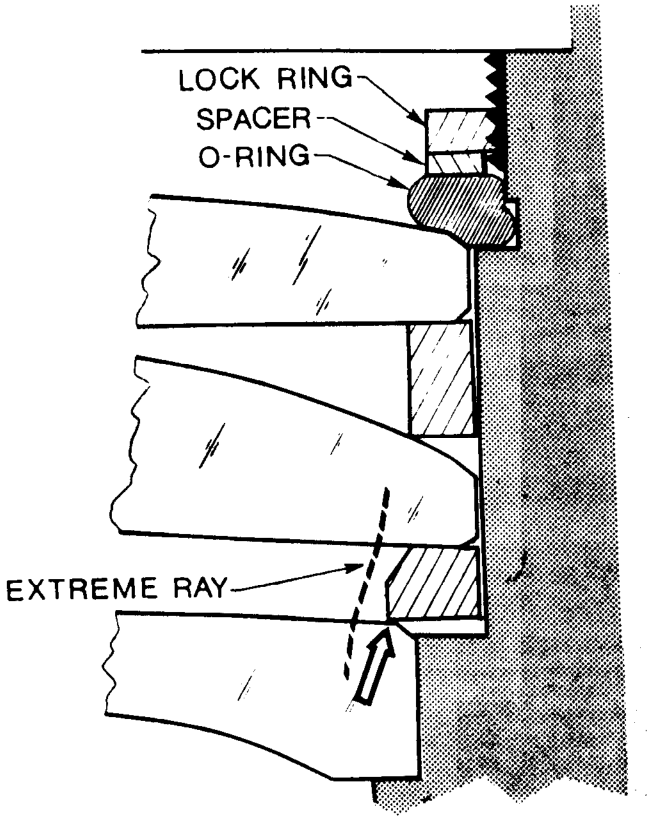

Fig. 8. Example of poor lens cell design with high stresses.

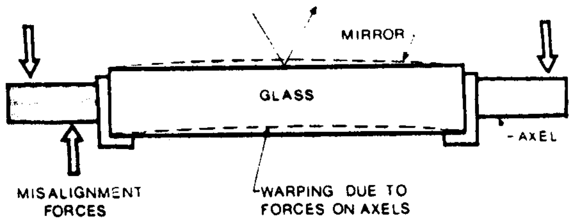

Fig. 10. Mirror warp due to forces on bonded axels.

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