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Design and fabrication of high performance relay lenses

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This paper deals with the design and fabrication of high performance doublets and triplets for relay lens applications. A Relay Lens by definition is simply a lens or lens system used to transfer a real image from one section of an optical system to another. This same lens form can of course be used as an objective lens. The design guidelines for these lenses are as follows:

A. $\frac{\lambda}{5}$ on axis for the completed lens assembly
B. Lens mounting to be as simple as possible e.g., lens mounted directly into a lens barrel
C. Overall cost important - lens must be assembled in somewhat of a production atmosphere.

Let me say at this point that I will not be talking about detailed design work as such. The selection of lens focal length, aperture, glass types and the balancing of aberrations I leave to the designer. What is more important are other considerations that affect the manufacturability of the item in question. I can assure you that to design a diffraction limited lens for the applications that I will be talking about is a significant task, but so is the task to build and deliver lens assemblies yielding the required performance. So I therefore wish to talk in brief about those areas in general that have a significant bearing on the overall performance of the finished lens.

Before getting down to specifics on the design and fabrication considerations, it is important to note the level of performance that can be achieved for lens assemblies and the resultant optical system.

The lens assemblies that I will be describing will be of relatively slow speed, let me say not faster than F/5, having a field of view not exceeding 5 degrees and corrected over the visual portion of the spectrum.

A typical triplet relay lens is shown in Figure 1. As you can see the lens elements are hard mounted into a lens barrel and secured in place by means of a clamp ring. It is important to note in this case that once the lenses are in the cell, there is no provision for adjusting one lens relative to another.

This particular lens assembly has a 100 mm aperture and is F/12. Figure 2 shows the quality that can routinely be achieved for such an assembly. Analysis of the interferogram yields an approximate wavefront error, measured peak to valley, of less than $\frac{\lambda}{10}$ single pass at .63 μ's.

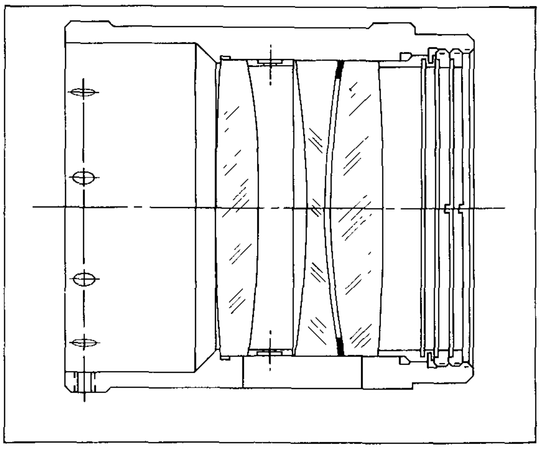

Figure 1. Triplet relay lens assembly

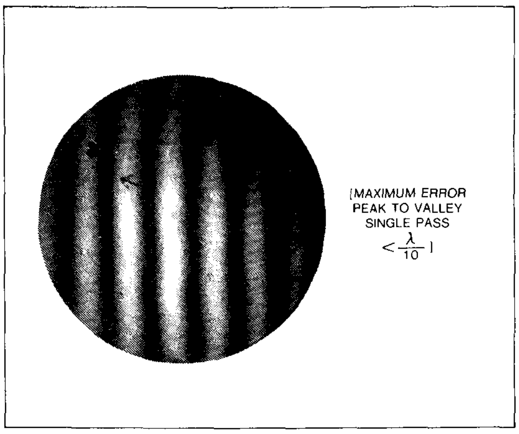

Figure 2. Interferogram of relay lens assembly (1200 mm EFL-F/12)

The programs at Kollmorgen where diffraction limited relay lens systems are used are mainly in Submarine Periscope Systems. A typical schematic of a periscope system is shown in Figure 3. This system is approximately 42 feet long and contains the lenses shown which are of various focal lengths and apertures.

Figure 4 shows the performance of such a system. As you can see the maximum wavefront error, again measured peak to valley, is approximately $\frac{\lambda}{5}$ to $\frac{\lambda}{4}$.

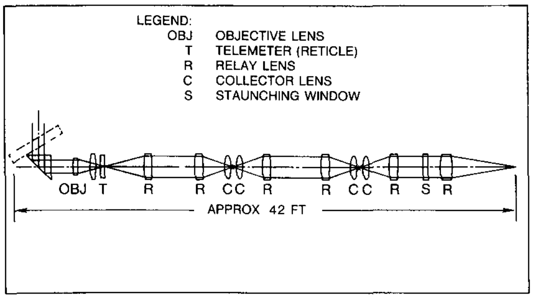

Figure 3. Optical schematic (periscope system)

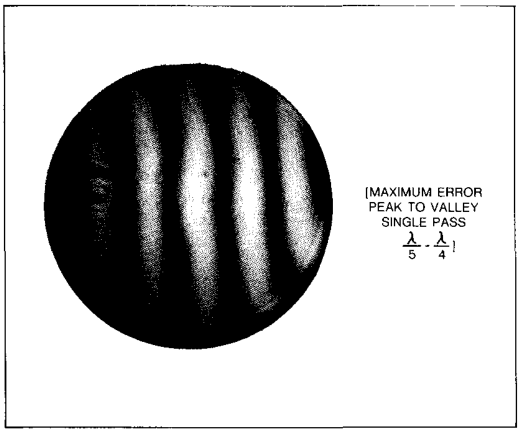

Figure 4. Interferogram of periscope system

The question that now remains is how does one proceed to design and fabricate lenses of this type and what factors are important?

To begin then, the type of design that is being discussed here is one, as mentioned earlier, where the construction is such that no adjustment is provided to position the lenses relative to each other in the lens assembly to achieve proper alignment. As a result it is extremely important that all the parts that make up the lens assembly are of very high quality, and this is a point that cannot be overemphasized. It is not to say that one cannot make a lens assembly perform correctly if parts are out of tolerance - both optical and mechanical, because you can. For example, if the type and amount of irregularity on each lens surface is known and you have enough lenses to choose from, you can select and match such that cancellation occurs, and the mechanical parts in some cases can be hand fitted. But all of this takes time, a lot of it, considerable expertise and good documentation. You can guarantee that lens breakage will increase and in the case of melt designed optics, for example the triplet, when you break one piece you in effect have lost the other two lens elements as well. And in addition, the overall schedule may be in trouble, especially if you are involved in a major program and have a large number of assemblies to build. Overall it becomes a very costly exercise.

To manufacture a precision lens assembly the following ingredients are necessary and are shown in Figure 5.

Each of these areas will now be discussed starting first with the design; considering various basic lens forms, their performance and sensitivity to small lens tilts and decenters.

Figure 6 shows two basic relay lens forms. One being the Conventional Doublet and Improved Doublet and the other being the Triplet. The Improved Doublet has a reduced secondary spectrum over the Conventional Doublet and the Triplet yields the ultimate with essentially zero secondary over the visual portion of the spectrum. It is important to note two important items at this point. The first is that the air spaces and lens shapes remain relatively constant during the design; that is they take a set form. Secondly, as the secondary spectrum is reduced by using other than the normal glass types such as in the Improved Doublet and Triplet the power of the individual lens elements increases, thus adding to their sensitivity to small tilts and decenters.

The optical designer at the beginning has the whole ball of wax. For it is out of this area that the overall requirements come. In the case of the Triplet (an apochromat) a glass search must be carried out. The tendency here is to use other than the ordinary glass types because of their peculiar partial dispersion characteristics for increased color correction. The designer must assure himself that the glass is available from the supplier in the size and having the proper homogeneity. He must concern himself with regard to the workability of the glasses, their stain classifications, transformation temperature and thermal coefficients. It would be desirable if a target budget was available so that performance could be weighed against cost. For example, an other than normal glass might take twice as long to polish and have a coating cost per lens of $200 as opposed to $40.

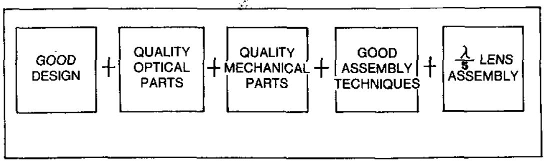

Figure 5. High performance lens ingredients

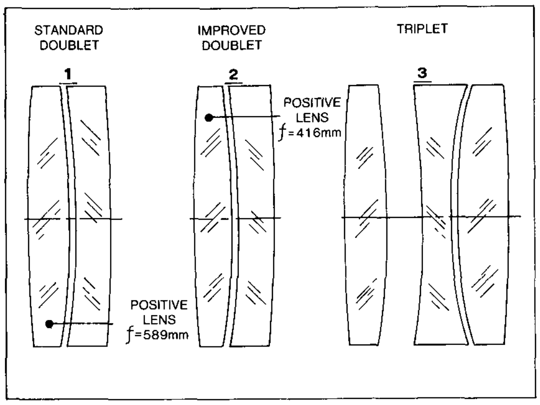

Figure 6. Relay lens configurations (1400 mm EFL, F/14)

As added information at this point, we at Kollmorgen find glass bought from Schott having a homogeneity classification of H2, that is $\pm 5 \times 10^{-6}$ adequate for our precision lenses. In the building of some 600 lens assemblies to date containing some 1800 or more individual lens elements Kollmorgen has yet to lose a lens assembly due to a problem associated with glass inhomogeneity.

To polish a lens in a minimum amount of time, no matter what the glass type, it must of course be rigid enough. Figure 6 shows lenses having good aspect ratios and adequate for polishing precision surfaces. It is also important to note that the larger the edge thickness of the lens the easier the lenses are to locate in the final assembly to yield optimum performance. In addition, when very little clearance is left between the lens O.D. and cell I.D. it is important that concave lens surfaces have sufficient edge bevels so that edge chipping does not occur during the assembly operation.

Tolerancing of course is an important part in any design effort and it is best arrived at through an experienced engineer who is familiar with optical and mechanical fabrication and assembly techniques. An inexperienced person could easily conclude that the lens was unbuildable or deserving of tight tolerances when in fact the reverse is true. Let me illustrate with the following example illustrated in Figure 7. The lens when it is assembled rarely experiences a decenter as shown. A tilt error would be more likely and is far less severe. This engineer is then your key person who can make the program a most successful one, for it is he who knows what will make the lens work or not.

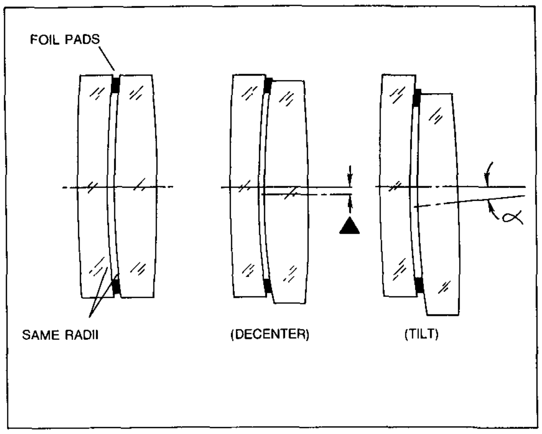

Figure 7. Tolerance analysis (typical example)

This leads to another important point and one which is important if not the most important and that is Communication - a single person such as the engineer I just mentioned must see that the information flows to all areas such as mechanical engineering, optical and mechanical fabrication, inspection, purchasing and assembly and that the information is interpreted correctly. The making of a successful program is people talking to one another and making sound compromises and tradeoffs.

Figure 8 compares the three lens types mentioned before with regards to their state of correction, sensitivity and diameter tolerancing.

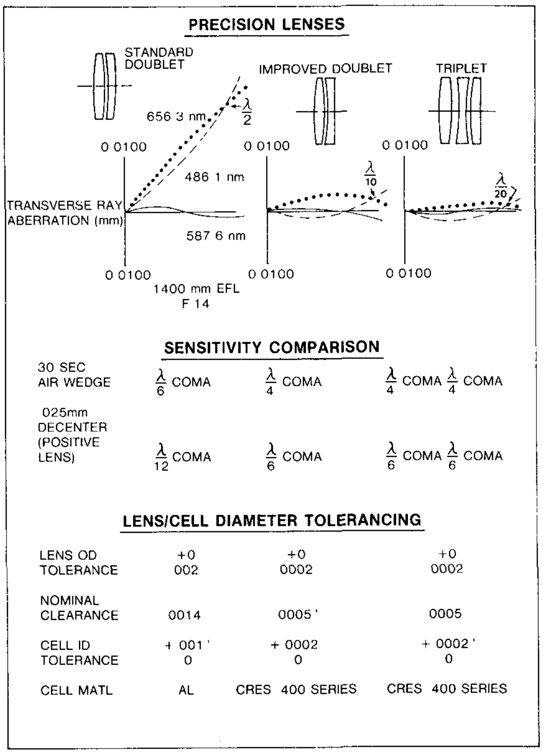

Figure 8. Lens performance, sensitivity, and diameter tolerance comparison

Figures 9 and 10 illustrate typical errors introduced in the lens assembly operation.

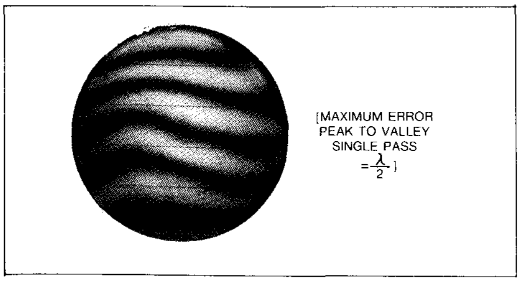

Figure 9. Interferogram showing typical errors (normal doublet)

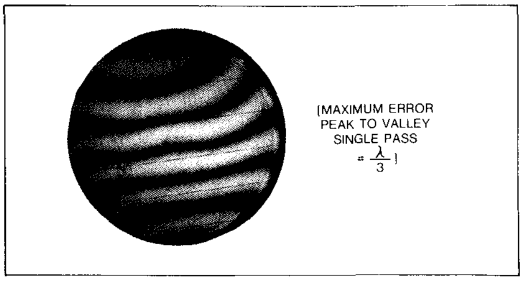

Figure 10. Interferogram showing typical errors (normal doublet)

Optical manufacturing is rather straightforward but there is one main area where problems can arise and it should be mentioned. This is the ability of a shop to evaluate a lens surface for small amounts of irregularity, that is 1/4 of a test plate fringe to say 1/8th. Before settling on a test method, one need evaluate the skill of the opticians, the quality of the test plates, the possible amount of residual power during test and the diameter to radius ratio of the lens surface. What I am saying here is that this area must be given adequate consideration at the onset of a program and one may in fact conclude that an interferometer surface test is necessary. I must also add that an experienced optician can produce 4 to 5 inch diameter optics to a 1/5 and 1/6th of a fringe even on strong surfaces having a radius to diameter ratio of 1.25 using test plates. On the other hand an interferometer directly in the optical shop and used by the optician making the optic is a very powerful learning tool and allows additional insight into the manufacturing process.

Before proceeding into the next area of consideration which is the mechanical parts manufacture, I need make a comment on what I think is the proper method for applying surface tolerances, that is the power and irregularity specification. In this regard, the engineer applying the tolerances should specify the irregularity tolerance he desires and then specify a liberal power tolerance according to the system needs. He should not use the standing ratio of 4 to 1 or 5 to 1 which seems to be the standard for the industry. The ratio should be more like 8 to 1 and the onus placed where it belongs, and that is on the optical shop to produce good parts. This is especially true with the manufacture of precision optics; to rework a precision lens surface, because it has a half fringe of excess power, is a very costly and heartbreaking exercise.

The mechanical design is as shown in Figure 1. The design as such is for a precision application and allows for minimum clearance between the O.D. of the lenses and the I.D. of the cell. The clearance is just sufficient to allow the lens assembly to survive military storage temperature at -65°F. The negative lens or flint in this case has the smallest thermal coefficient and is squeezed by the cell at low temperatures. The cell and spacer material is 400 Series Cres to provide the best thermal match with the glass and in addition is corrosion resistant. The tolerancing for the lens and cell is as described on one of the previous slides.

All parts are rough machined, heat treated, then finished machined and receive a black oxide coating.

The lens cell is ground on the I.D. and checked for diameter before and after the black oxide application using a plug gauge. The lens cell must be perfectly round and the lens seat square to the bore for it to work properly. The measure of a good cell is one where the plug gauge, when inserted into the cell in the vertical position, freely floats to the bottom of the cell under its own weight and acts much like a piston.

Probably the most difficult part to manufacture is the lens spacer and in addition is one of the most important. A good spacer is one that is perfectly round, not elliptical, and whose faces are square to the O.D. There are many ways in which a spacer like this can be fabricated but let me explain a method in which we have found good success.

Figure 11 illustrates the first step. The spacer is rough machined to near finish dimensions and heat treated.

Figure 12 illustrates the second step. The spacer is potted into a fixture as shown using a low melting alloy. The I.D. of the spacer is then bored to its final diameter.

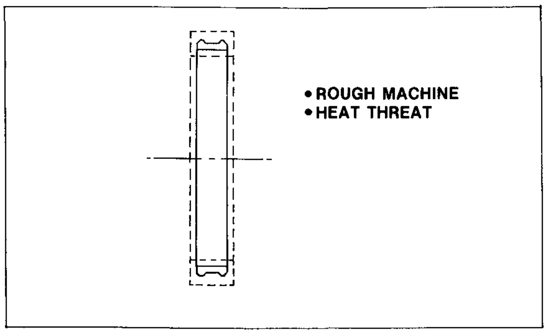

Figure 11.
Lens spacer fabrication (step 1)

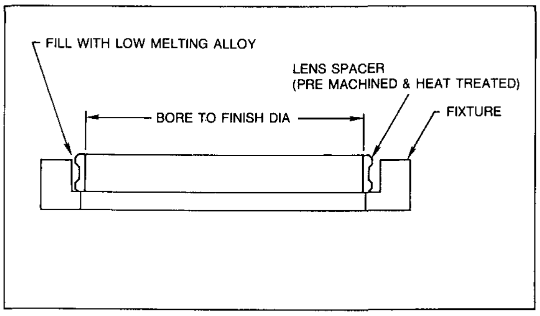

Figure 12.
Lens spacer fabrication (step 2)

Figure 13 illustrates the third step. A number of lens spacers are then slipped over a precision arbor and ground to the finished diameter.

Figure 14 illustrates the fourth step. The lens spacer is placed into a precision ring and the top surface ground flat. The spacer is then turned and the opposite side ground flat and then turned once more and ground to the finished dimension.

The completion of this operation yields a finished lens spacer, perfectly round with faces that are square to the O.D. and more than adequate for building precision lens assemblies.

At this point I would like to add that the manufactured optical and mechanical parts must be stored properly which is a condition that is often overlooked. Each item should be in its own protective container to protect against poor handling.

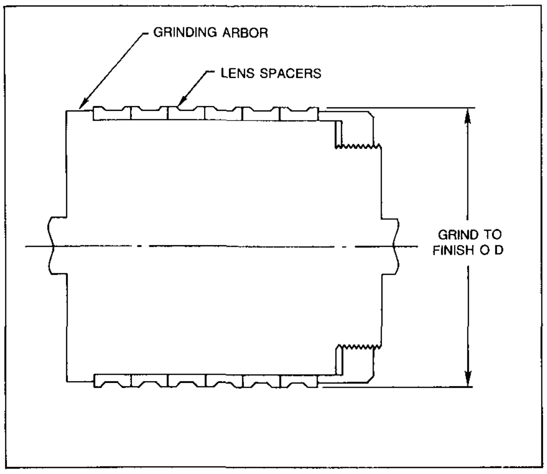

Figure 13.
Lens spacer fabrication (step 3)

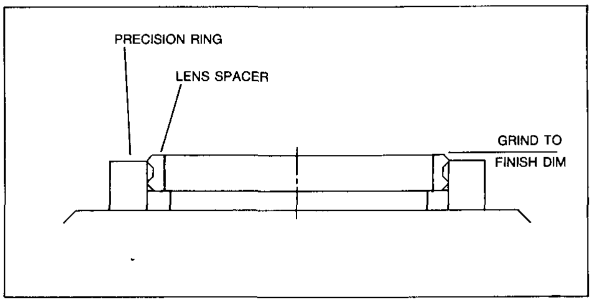

Figure 14.
Lens spacer fabrication (step 4)

The final step is assembly and here this operation is as critical as manufacturing the optical and mechanical parts. The most important factor is the selection of a person to do the assembly work. This person must have good natural mechanical ability, the ability to think and learn and have demonstrated it in the past and there is usually one individual like this in every organization. The problem here is to get him assigned to your program.

This individual must then be given the information and tools to work with. He must receive an in-depth discussion from optical engineering with regard to the sensitivity of air spaces in the lens assemblies, the effect of small tilts and decenters and an understanding regarding surface quality. I would also suggest a surface plate, dial indicators, a torque wrench for setting clamp ring pressure and a set of plug gauges for the various lens cells, and finally, but not least, an interferometer to be used as an assembly tool. The interferometer in this case is the one indispensable tool and can be used to assess everything from excess clamp ring pressure to the effect of marginal parts.

Figure 15 indicates lens assembly hours vs. lens speed or F/NO. As you can see the faster the lens the more difficult it is to assemble and that around F/7 or F/8 the lens form changes from a triplet to a four element lens. The times shown here are average assembly times that can be expected and include the following:

A. Cleaning and assessment of mechanical parts
B. Cleaning of optical parts
C. Two assembly operations because you usually don't get exactly what you want on the first try or based on the evaluation of the interferogram you know you can improve the quality so you make the attempt
D. Evaluation of final assembly and documentation

Finally what does all this cost? Figure 16 illustrates normalized manufacturing hours vs. the various work centers. As you can see the cost of the Improved Doublet and Triplet are somewhat greater than for the Normal Doublet.

When looking at Figure 16, the question that arises is whether there is a way to improve performance, reduce cost or both? The mechanical design, as shown in Figure 1, has been employed now for some 15 to 20 years in submarine periscope programs, and was at the time thought to be the most cost effective and do-able from a production point of view. But what about today? If we were tasked with the mechanical design now would we approach it any differently? I believe the answer is yes and let me present one new approach for consideration, that is, using Single Point Diamond Turning techniques for producing precision mechanical components.

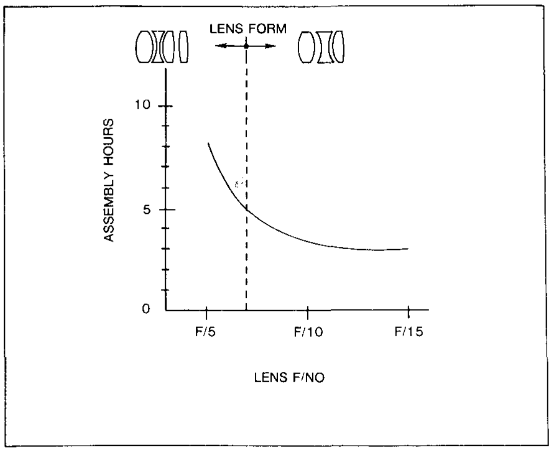

Figure 15. Lens assembly hours vs. lens F/NO.

	NORMALIZED MANUFACTORING HRS		
	NORMAL DOUBLET	IMPROVED DOUBLET	TRIPLET
MECHANICAL FAB	1	2 5	3
OPTICAL FAB	1	3	4
INSPECTION	1	2	3
ASSEMBLY	1	4	6

Figure 16. Manufacturing hours vs. work center

It is important, however, to look first at the type of mechanical tolerances we are faced with in the current design. Figure 17 and 18 illustrate typical tolerancing from both the lens cell and lens spacer.

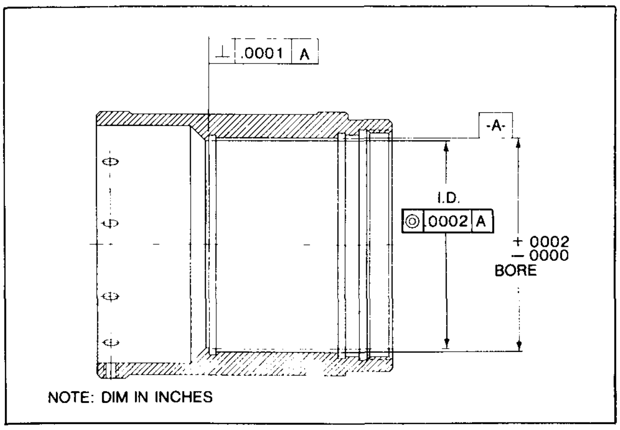

Figure 17.
Typical Lens Cell Tolerancing

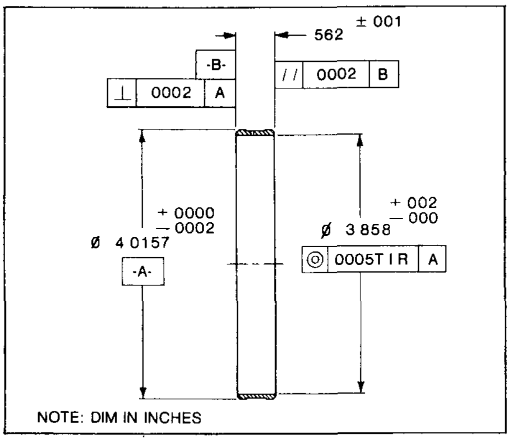

Figure 18.
Typical Lens Spacer Tolerancing

The ability to achieve success in building a good lens assembly depends greatly on how well the lens spacer and lens cell can be fabricated. Figure 19 illustrates a new approach to the cell design in that the lens spacer is integral and part of the lens cell. This concept has one significant advantage in that it eliminates the machining of the thin walled spacer element shown in Figure 18.

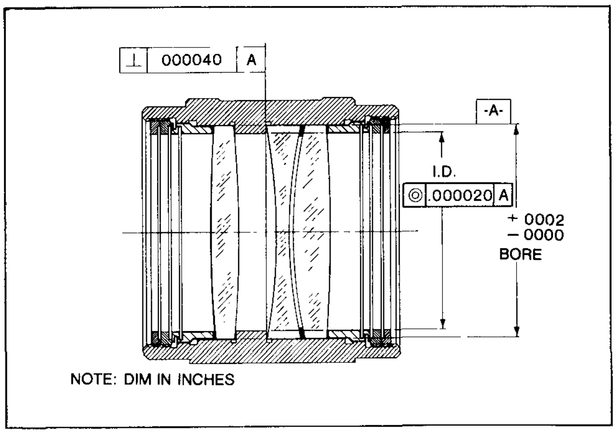

Figure 19. Improved Cell Design and Tolerancing

In addition to the proposed change in cell design one need also consider a change in the machining process to fabricate the lens cell. The proposed new process would utilize Single Point Diamond Turning using a Diamond Turning Machine incorporating an air bearing work spindle and air slide. The normally used natural diamond tool would be replaced with a cubic boron nitride tool (CBN) for cutting ferrous metals.

Let us now look at the typical machining tolerances that can be held using the new machining process. Figure 19 depicts the tighter tolerancing and increased accuracy obtainable from the new method.

It is estimated that the overall mechanical parts fabrication cost would be less for the new proposed design and new fabrication process. In addition, the accuracy of the lens cell would be improved resulting in increased lens performance with reduced effort during the assembly operation.

In summary, high performance relay lenses require not only a superior optical design but superior mechanical mounting techniques combined with excellent workmanship to achieve the desired results. In addition, the use of Single Point Diamond Machining Technology offers a new and exciting process for application into these systems for increased performance and reduced cost.