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The design and assembly of camera lens cells for fluid couplants using elastomeric lens mounts

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1.0 ABSTRACT

The DEIMOS camera includes two doublets and one triplet lens groups. The interstices between these elements need to be filled with a couplant. After much experimentation, it was determined that the best type of couplant was a fluid. The primary design challenge using fluid couplants is providing proper sealing so that the fluid does not leak out over time. One approach is to pot the lenses into their cells. This not only supports the lenses but it also provides a continuous seal between the lenses and the cell. This report describes the design and assembly processes developed by the lab personnel at Lick Observatory. The intent is to give a step by step description of this technique.

2.0 INTRODUCTION

DEIMOS is a wide-field, faint-object spectrograph for the Keck II telescope. The cameras are large, nine element devices made from exotic materials (see Figure 1). There are two doublets and one triplet in the camera. The design calls for the gap between the lenses of the multiplets to be filled with a couplant. We experimented with three types of couplants; an elastomeric gel, grease, and fluid. The first doublet and the triplet contain elements made from calcium fluoride. This crystalline material has a much larger coefficient of thermal expansion than the materials used for the adjacent elements. This large difference of expansion coefficients and the large sagitta of the design contributed to the gel and grease failing during thermal cycling tests. The couplants were not compliant enough to accommodate the large changes in radii of curvature experienced during the changes in temperature. The couplants failed in shear and long thin air bubbles penetrated inwards from the edges. This led us to the use of fluid couplants. The specific couplant used in our experiments was Dow Corning 200 Fluid, 1000 centistoke viscosity. The primary disadvantage of fluid couplants was the difficulty in making adequate seals to prevent the couplant from leaking out and migrating onto the optical surfaces.

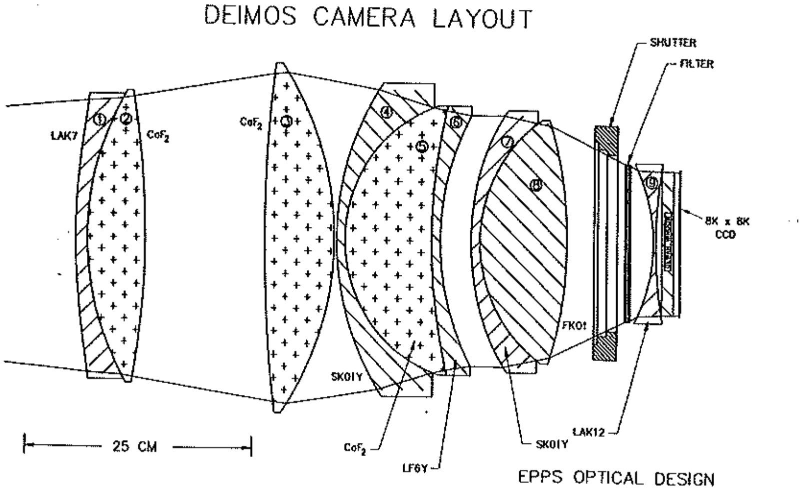


Figure 1

Once the decision to use a fluid couplant was made, several design studies were made to solve the sealing problem using o-rings. It was at this point that Dan Fabricant of Harvard-Smithsonian Center for Astrophysics suggested using elastomeric lens mounts. He and Robert Fata had done some work using elastomeric mounts on the MMT. Whereas their design uses numerous elastomeric pads to support their lenses, we reasoned that a continuous elastomeric bead would provide not only physical support, but a seal for the couplant as well. This decision led to almost a year of design work and experimentation to develope the technology to both design and fabricate this type of lens mount.

3.0 ADVANTAGES

The traditional method of mounting a lens into a cell is with six solid mounts, one set of three for the axial direction and another for the radial direction. The elastomeric mounts, being continuous,distribute the forces much more evenly around the perimeter of the lens and thus causing less distortion.

The other obvious advantage is that the continuous bead of elastomer forms an effective lens-to-cell seal for the couplant.

4.0 DESIGN OVERVIEW

Figure 2 shows the design of a cell for a test doublet that was used for our research.

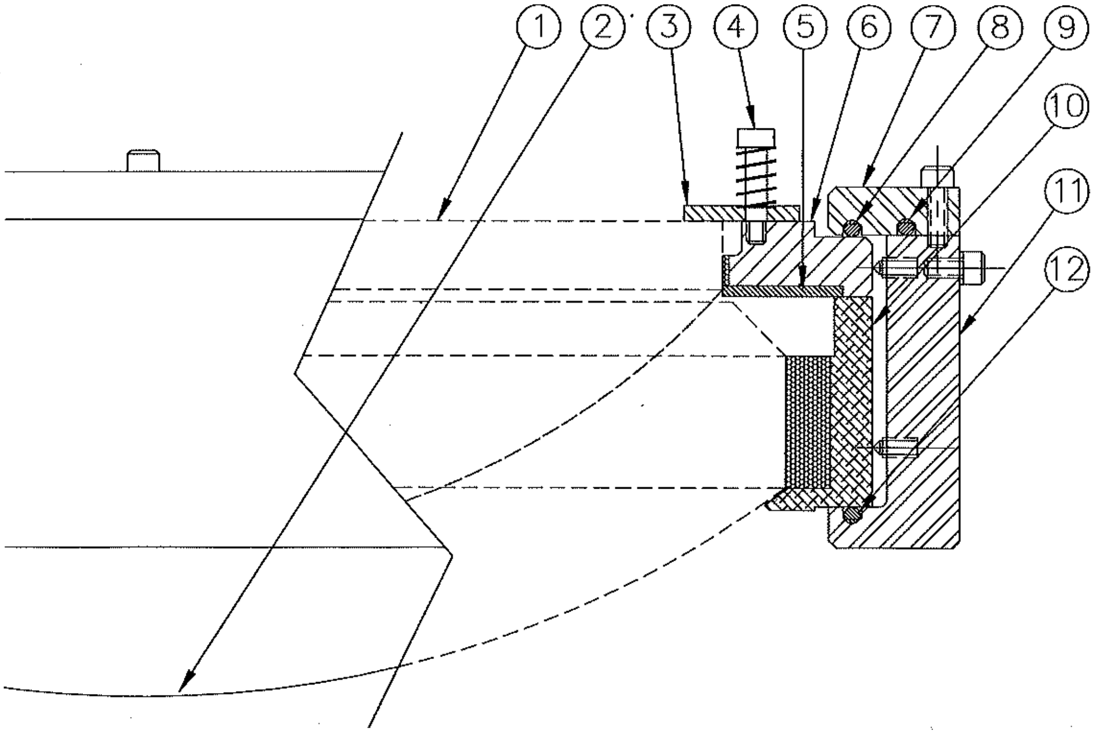


Figure 2

The upper lens (item 2) is the calcium fluoride lens. There are inner and outer cell assemblies. The inner cell consists of two rings (items 6 and 10), one for each lens element. The couplant fills the gap between the lenses as well as the void between the two inner cells. The elastomeric bead prevents the couplant from moving between the ring and lens. Channels between the two rings allows the couplant to flow radially outwards. The o-rings (items 8, 9, and 12) on the outer cell prevent the couplant from escaping out of the cell assembly. Item 5 is a dam, explained later, that is used in the casting phase only and is removed after the elastomer has set up. Item 3 is a spring loaded retaining ring that provides the axial load necessary to keep the lenses in place axially.

5.0 ELASTOMERS

Research done by Robert Fata and Dan Fabricant[1] determined that the best elastomer for this application is RTV560 made by GE Silicones. We did not research any alternatives as the RTV560 seemed to provide the needed properties.

6.0 ATHERMALIZATION

Fixing the lenses to the aluminum rings involves matching three different coefficients of thermal expansion. The concept is that the aluminum ring will expand faster than the lens. The gap dimension between the lens and the cell should be chosen so that the elastomer will expand exactly enough to fill the gap as it increases with the rising temperature. Yoder[2] gives the formula for computing the gap dimension as:

$$t_E = \frac{D_G(\alpha_M - \alpha_G)}{2(\alpha_{RTV} - \alpha_M)}$$

Where:

t_E = radial thickness of elastomer bead (inches)

D_G = lens element diameter (inches)

α_M = coefficient of thermal expansion of the metal cell (inch/inch/°C).

For aluminum: $\alpha_M = 23.0 \times 10^{-6}$.

α_G = coefficient of thermal expansion of the lens (inch/inch/°C)

α_{RTV} = coefficient of thermal expansion of the elastomer (inch/inch/°C)

All of these properties are readily determined except for α_{RTV}. The coefficient of thermal expansion for an elastomer is not constant but is a function of what is called the shape factor. The shape factor is explained in the section dealing with calculating the bead dimensions.

7.0 LENS DECENTERING DUE TO GRAVITY

The DEIMOS camera's optical axis oscillates between + and - 2.3 degrees from horizontal. This means that the weight of the lens is always in primarily a radial direction. The radial forces cause the lens to move by compressing the elastomeric bead. This motion, called decentering can be predicted by the following formula, again from Yoder:

$$\Delta = \frac{AWt_E}{\pi R d\left[\left(\frac{E_C}{1-v^2}\right) + E_S\right]}$$

Where:

Δ = decentration of lens (inches)

A = radial acceleration (= 1 if just gravity load)

W = weight of the lens (pounds)

t_E = radial dimension (thickness) of the elastomeric bead (inches)

R = lens diameter (inches)

d = axial dimension (width) of the elastomeric bead (inches)

E_C = modulus of elasticity of the elastomeric bead (psi)

v = the Poisson's ratio of the elastomer

E_S = the shear modulus of the elastomer

As with the formula for athermalizing, most of these properties are readily found except for the ones for the elastomer (E_C, v, and E_S). The Poisson's ratio of elastomers is fairly constant at about 0.50. The shear modulus for RTV560 is 117.5 psi. The elastic modulus, like the coefficient of thermal expansion is a function of the shape factor.

8.0 AXIAL FORCES

Since the optical axis is always nearly horizontal, the gravity vector in the axial direction is negligible. The primary loading of the lenses in the axial direction is caused by the hydrostatic forces from the couplant. This load varies with the height of the couplant from zero at the top to the maximum load on the bottom. As DEIMOS rotates, the location of the top and bottom points also rotate.

It was found that the elastomeric beads were insufficiently stiff in the axial direction to be relied upon for the axial placement. We use the traditional 3 hard point positioning system to locate one of the lenses. Three shims of the proper thickness (we use .003 inches) are placed on the outer edge of the glass between the elements. There are springs which compress all of the lenses against the three axial hard points.

9.0 DESIGNING THE BEAD DIMENSIONS

9.1 Introduction

The design of the bead dimensions is an iterative process. The goals are to find a radial dimension (thickness) that satisfies the athermalization equation and an axial dimension (width) that satisfies the decentering equation. It is desired that all of the lenses decenter approximately the same amount.

9.2 The Shape Factor

All of the terms in the athermalization equation are known except for α_E which is a function of the shape factor. All of the terms in the decentering equation are known except for E_C which is also a function of the shape factor. The shape factor is defined as the ratio of the loaded area (single face) divided by the force free area. For a bead that completely encircles the lens with no gaps, the shape factor, S, is simply:

$$S = \frac{width}{2 \times thickness}$$

9.3 The Equations.

The corrected modulus of elasticity, E_C, for an elastomer is:

$$E_C = E_o\left(1 + 2kS^2\right)$$

The E_0 (initial modulus of elasticity) for RTV560 is 478.5 psi.

The k (material factor) for RTV560 is 0.64.

Using this equation and given the shape factor, the E_C can be easily computed.

The effective coefficient of thermal expansion of the elastomer (α_{RTV}) is:

$$\alpha_{RTV} = \alpha_0 K_T$$

The initial coefficient of thermal expansion (α_0) for RTV560 is 198 x 10^{-6}/°C. K_T is a correction factor for the coefficient of thermal expansion. K_T varies with the shape factor, S. Unfortunately, unlike E_C which can be computed directly, K_T must be taken from a graph of empirical data. This graph, presented by Lobdell[3], (Figure 3) shows a curve of S versus α_t (α_t is what we have been calling α_{RTV}.). The data is for RTV11 rather than RTV560 but Fata and Fabricant feel that it is safe to use the RTV11 data for other RTVs since the thermal correction factors do not vary significantly. To find K_T, find S on the horizontal scale and then find the corresponding α_t on the curve. $K_T = \alpha_t/\alpha_0$. Remember to use α_0 for RTV11 (148 x 10^{-6}/°F). This is a confusing area of the calculation since we are dealing with two different α_0 's here. Also note that the Lobdell data is using Fahrenheit where we had been using Centigrade. Be especially careful to avoid getting these figures mixed up.

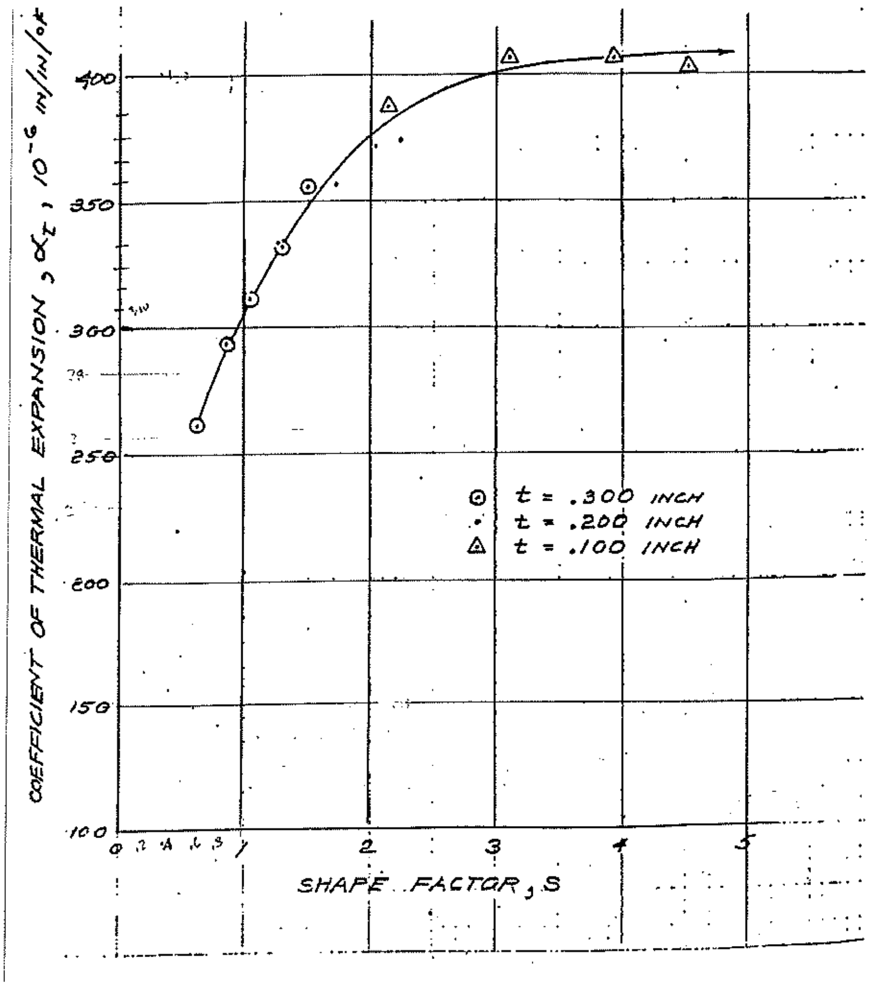


Figure 3

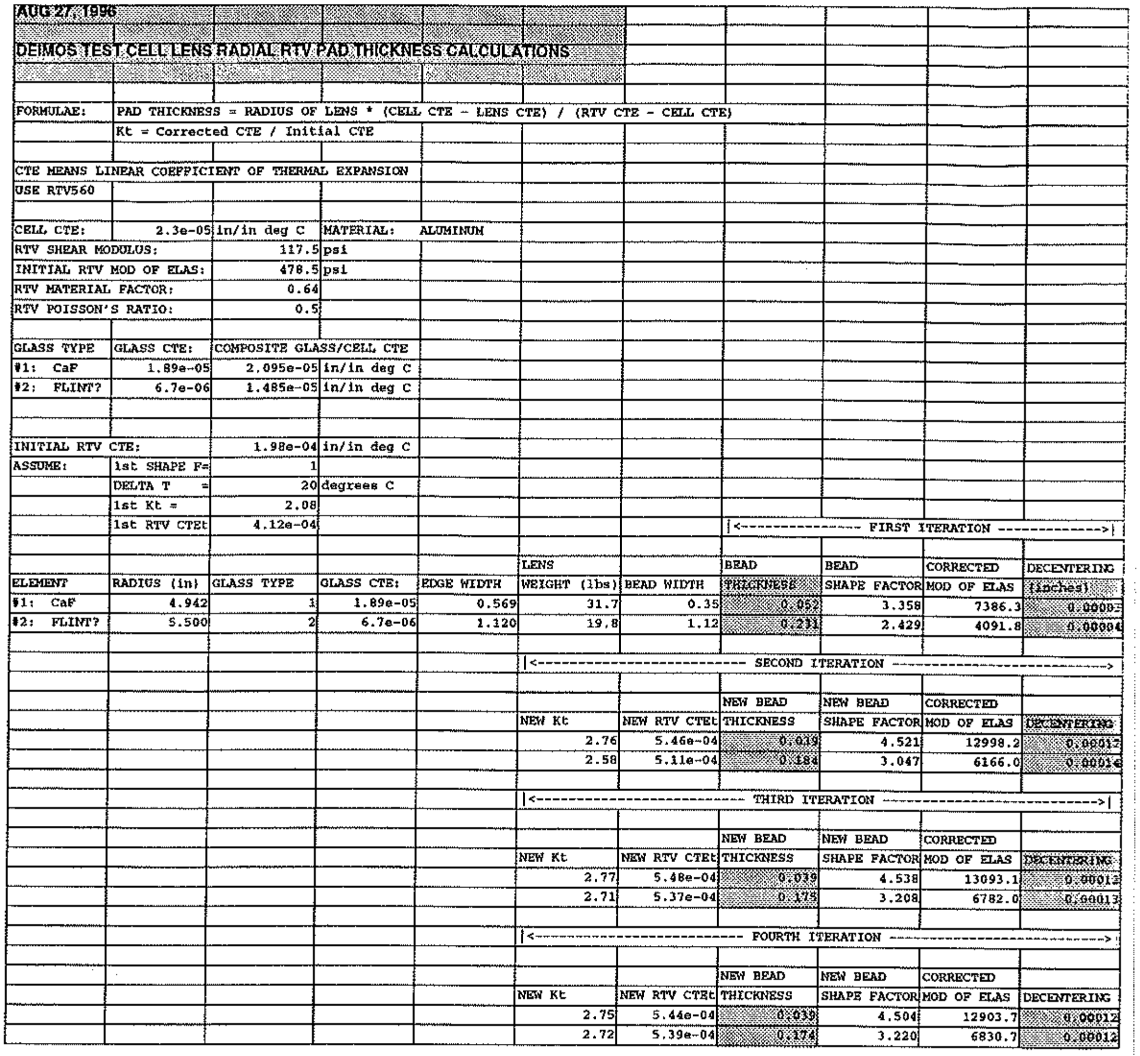
9.4 Calculating the Bead Dimensions.

9.4.1 Setup.

Now that we have developed the necessary equations, the procedure from here on is tedious but straightforward. We have found that the easiest method is to set up the data in tabular form using a spreadsheet computer program (see Figure 4). First, list all of the constants that will be used in the calculations. Second, list all of the assumptions needed to begin the calculations. We assumed an initial shape factor of 1 for the first iteration. Second, make a table of each of the elements and their properties. In this table, assign a bead width for each element. For the first try, We used .25 inches. One must remember that there is a limitation on the bead width in that it can never exceed the edge width of the lens that it is supporting.

9.4.2 First Iteration:

First, calculate the α_{RTV} using $S = 1$ and the graph in Lobdell's paper. Next compute the bead thickness, t_E, using α_{RTV}. Third, find the new shape factor. S. Fourth, calculate E_C using the new S. Finally, compute the decentering, Δ.



AUG 27, 1996

DEIMOS TEST CELL LENS RADIAL RTV PAD THICKNESS CALCULATIONS

FORMULAE: PAD THICKNESS = RADIUS OF LENS * (CELL CTE - LENS CTE) / (RTV CTE - CELL CTE)
Kt = Corrected CTE / Initial CTE

CTE MEANS LINEAR COEFFICIENT OF THERMAL EXPANSION
USE RTV560

CELL CTE:	2.3e-05	in/in deg C	MATERIAL:	ALUMINUM
RTV SHEAR MODULUS:	117.5	psi		
INITIAL RTV MOD OF ELAS:	478.5	psi		
RTV MATERIAL FACTOR:	0.64			
RTV POISSON'S RATIO:	0.5			

GLASS TYPE	GLASS CTE:	COMPOSITE GLASS/CELL CTE	
#1: CaF	1.89e-05	2.095e-05	in/in deg C
#2: FLINT?	6.7e-06	1.485e-05	in/in deg C

INITIAL RTV CTE:		1.98e-04	in/in deg C
ASSUME:	1st SHAPE F=	1	
	DELTA T =	20	degrees C
	1st Kt =	2.08	
	1st RTV CTEt	4.12e-04	

|<-------------- FIRST ITERATION ------------>|

ELEMENT	RADIUS (in)	GLASS TYPE	GLASS CTE:	EDGE WIDTH	LENS WEIGHT (lbs)	BEAD WIDTH	BEAD THICKNESS	BEAD SHAPE FACTOR	CORRECTED MOD OF ELAS	DECENTERING (inches)
#1: CaF	4.942	1	1.89e-05	0.569	31.7	0.35	0.052	3.358	7386.3	0.0000
#2: FLINT?	5.500	2	6.7e-06	1.120	19.8	1.12	0.231	2.429	4091.8	0.00004

|<------------------------ SECOND ITERATION ------------------------>

NEW Kt	NEW RTV CTEt	NEW BEAD THICKNESS	NEW BEAD SHAPE FACTOR	CORRECTED MOD OF ELAS	DECENTERING
2.76	5.46e-04	0.039	4.521	12998.2	0.00017
2.58	5.11e-04	0.184	3.047	6166.0	0.0001

|<------------------------ THIRD ITERATION ------------------------>|

NEW Kt	NEW RTV CTEt	NEW BEAD THICKNESS	NEW BEAD SHAPE FACTOR	CORRECTED MOD OF ELAS	DECENTERING
2.77	5.48e-04	0.039	4.538	13093.1	0.00013
2.71	5.37e-04	0.175	3.208	6782.0	0.00013

|<------------------------ FOURTH ITERATION ------------------------>

NEW Kt	NEW RTV CTEt	NEW BEAD THICKNESS	NEW BEAD SHAPE FACTOR	CORRECTED MOD OF ELAS	DECENTERING
2.75	5.44e-04	0.039	4.504	12903.7	0.00012
2.72	5.39e-04	0.174	3.220	6830.7	0.00012

Figure 4

9.4.3 Subsequent iterations.

Using the new S, find the new K_T, and compute the new α_{RTV}, and t_E. Using the new t_E, calculate the new S. At this point, compare the new S with the previous S to see how much it has changed. We found that after about 5 iterations, the S value began to converge on a value. When you are satisfied that the change in S is negligible, use the last S as the final value. Now compute the final E_C and Δ.

9.4.4 Do the same iterations for each of the elements.

9.4.5 Fine tuning the decentering.

Remember that one of the goals is for all of the elements to decenter approximately the same amount. Compare the decentering for all of the elements. The decentering can be increased by decreasing the bead width or decreased by increasing the bead width. Adjust the bead widths as necessary (remember not to exceed the lens edge width) and redo all of the calculations. When you are satisfied, you will have the final bead dimensions for each lens.

10.0 CASTING TECHNIQUES

10.1 WICKING

To cushion the glass to metal interface at the axial registration surface, we placed three small pads of plastic tape at 120° intervals. This tape is about .002" thick. The RTV easily wicked into the .002" gap between the pads but did not lift the glass off of the pads. The result is that the glass was still being registered by the three pads but was supported all around the ledge by the RTV.

10.2 AXIAL AND RADIAL ALIGNMENT

When casting a multiplet, the lenses are cast one at a time. In all of our cases, the first lens is held axially by a ledge on the cell. The first lens is placed on the plastic pads which automatically align it axially. Radial alignment is accomplished by carefully measuring the gap between the cell and lens using a gauge pin. The appropriate gauge pin will just fit in the gap and not move the glass as it is slid around the circumference. When the appropriate gap is determined, two of this size pin are attached to a bar so that they are held in place at approximately 120° apart in the gap (figure 5). The lens is then slid up against the two pins. The first lens is now aligned axially and radially. Remove the pins and cast the first lens mount.

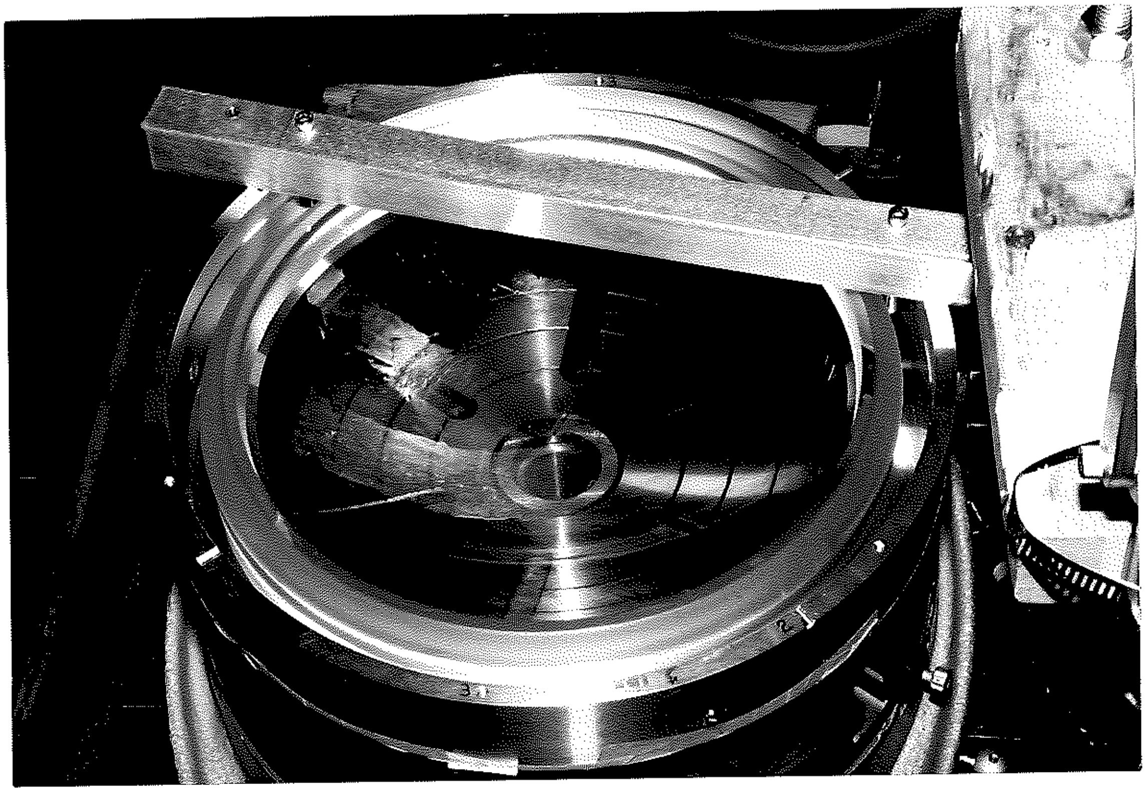


Figure 5

After the first lens is cast, a set of three shims of the appropriate thickness (in our case .003") is placed on the mating surface. The shims are strips of mylar shim stock which are held in place by screws set into the cell. When setting the clocking position of the shims, they should line up with the pads holding the first lens. This ensures that the axial forces are conducted in a straight line through the multiplet and bending stresses are not introduced into the lenses. Next, the second lens and its dam are placed onto the shims. The shims are now axially locating the second lens. The radial alignment is done in the same way as the first lens. When the alignment is satisfactory, cast the second lens.

Subsequent lenses are cast in the same manner.

10.3 DAMS

When casting the elastomeric bead supports, the lower edge of the bead is formed by either the axial supporting ledge or by a peripheral dam (see figure 2, item #5). The idea is to have the center of gravity of the lens pass as closely through the center of the bead as possible. Often, this means casting the bead near the side of the lens that has the convex surface. In the case where the lens is held by the axial registration ledge on the cell, the ledge is used to form the lower edge of the bead. In other cases, rings were made from plastic sheet to a close tolerance fit with the outside diameter of the lens. These rings then act as dams to form the lower edge of the bead. The RTV will wick into the small gap between the dam and the glass but stops before running out beyond the dam. The dam is held in place either by capturing it between the cells or by screwing it to the upper cell. After the RTV has cured, the dam is removed.

10.4 PREPARATION

The surfaces to which the RTV needs to bond must be cleaned thoroughly and primed with SS4004 silicone primer. To protect exposed lens surfaces, they can be coated with 3M strip coat.

10.5 MIXING

RTV 560 is a two part compound which requires mixing. There are two possible curing agents depending on the application. We used STO as opposed to DBT. The two parts must be weighed out and mixed according to the instructions provided with the kit.

10.6 DEGASSING

After mixing, the RTV is placed in a bell jar and the pressure is drawn down to an absolute pressure of 25 mm of mercury and kept until the mixture stops frothing (figure 6). Be sure to use a large enough container as the volume will increase by about 4 to 5 times the original volume until all the air has escaped.

Figure 6

10.7 DISPENSING

Dispensing the liquid RTV neatly and evenly can be challenging. The technique which we found to be the most effective was to use a 60 cc syringe (figure 7) placed in a holder of our own design. The holder has a threaded plunger which advances as a screw is turned (figure 8). Depressing the plunger by hand is very tiring and produces uneven results. The holder is in turn held in a stationary jig so that the tip does not move with respect to the lens and cell. The cell is mounted on a motorized rotary table which turns the cell at a constant speed. The RTV leaves the tip in a thick stream and falls into the gap (figure 9). If the flow rate is kept low enough, the RTV will fall straight down into the gap. If the flow is too fast, the stream will oscillate causing it to hit the walls of the gap and giving an uneven and messy result.

10.8 CURING

The nominal curing time is 24 hours, depending on the mixture ratio and ambient air temperature. However, tests of plugs of the mixture showed that the thicker sections of RTV will cure more slowly and from the outside in. Some section that were a little over 1/2" thick took up to 5 days to cure completely at room temperature.

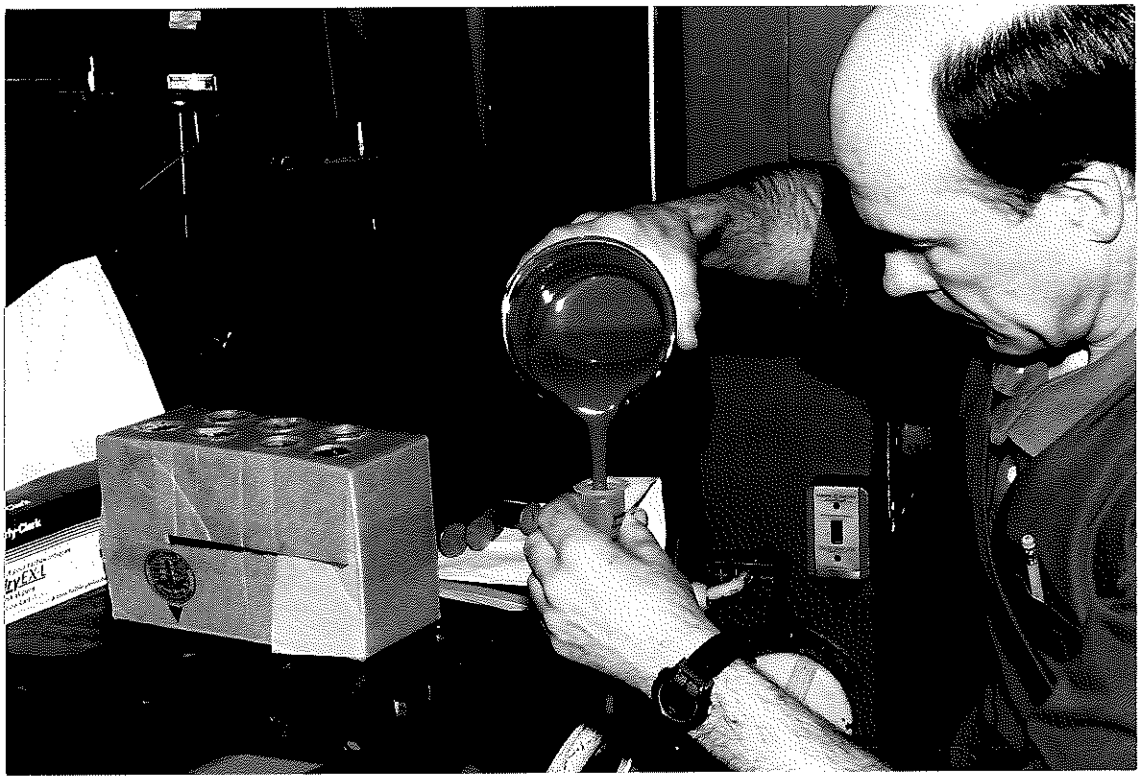


Figure 7

Figure 8

Figure 9

11.0 CELL MECHANICAL FEATURES

11.1 AXIAL REGISTRATION AND RESTRAINT

This design does not rely on the elastomeric bead for axial registration. As was mentioned in the design overview, The lenses are positioned axially by mechanical hard points on the first surface, by shims between the second and third surfaces and spring loaded soft points on the last surface. The hard points consist of three pieces of .002" thick cellophane tape which were placed on the continuous axial shelf on the first inner cell ring (see Figure 2, item 10). It was found that when the RTV was cast into this area, it wicked into the .002" gap between the hard points. There was still contact at the hardpoints but now we had a conformal axial support all the way around the lens. This is considered a fortunate benefit.

As in normal cell design the hard points and shims should be placed one above the other so that there is direct compression through the entire multiplet. If these should be misaligned, the lenses will experience bending stresses.

11.2 RADIAL REGISTRATION AND SUPPORT

The lenses are supported radially by the RTV beads which are in turn supported by the inner cell rings. Due to the interlocking curved surfaces the lenses cannot move radially with respect to each other without rotating about their center of curvature. But the lenses and the inner rings can move radially as a unit with respect to the outer cell. The relative position of the inner rings to the outer cell is controlled by radial set screws set in the outer cell. The tapped holes for these set screws need to be plugged on the outside to prevent the couplant from leaking around the set screws and migrating outside the cell.

11.3 O-RING SEALS

The o-rings are viton which we have found to be the most durable. Viton is also compatible with the silicone based couplants we are using. The seals between the inner rings and outer cell are face seals so that radial adjustment is still possible. The seal between the two parts of the outer cell may be any type. Standard gland designs were used.

11.4 FLUID INSTALLATION AND BLEED VALVES

There are three ports in the outer cell (not including the holes for the radial adjustment screws) as shown in Figure 5. One of the ports is for the volume compensator which is discussed later. The other two are the bleed valves. These are standard automotive brake system bleed valves. A small o-ring was placed at the bottom of the cavity for assured sealing. The purpose of these valves is to install the couplant. The couplant goes into one of the valves and the air is bled out the other valve. The valves should be placed fairly close together as they both need to be near the top when the couplant is installed.

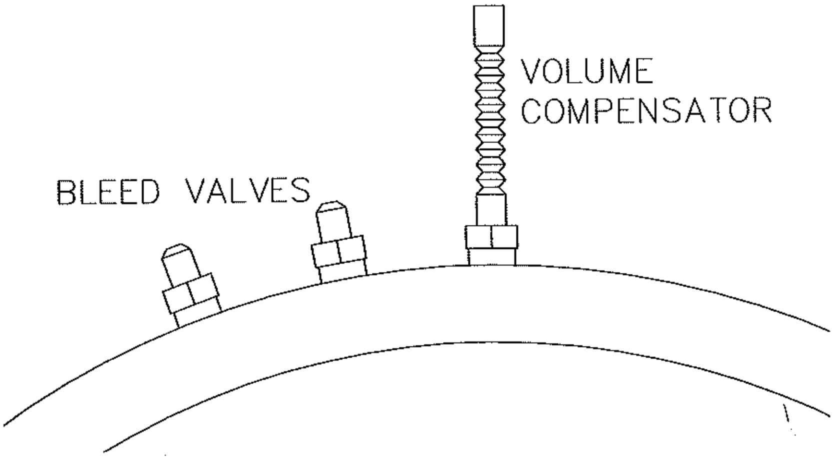


Figure 5

11.5 VOLUME COMPENSATION

The volume compensator is a flexible metal bellows that is closed on one end and attached to a fitting on the other. The compensator is a small expandable reservoir for the couplant. As the fluid expands and contracts due to temperature changes, the changes in volume are taken up by the compensator. We made the one for our experiments from scrap pieces, but they can be purchased from the Servometer Corporation, Cedar Grove, New Jersey.

11.6 ELASTOMER LEVEL FIDUCIAL

Referring again to Figure 2, you will notice a step in the inner diameters of the inner rings at the top of the RTV bead. This does several things. First, it indicates the desired level of RTV when casting the bead. Second, it helps to ensure that the RTV surface is level and flat. Third, any RTV that extends beyond the step has no support from the recessed surface of the inner ring and thus becomes non-structural.

11.7 DAM COUNTERBORE

Item 5 on Figure 2 is a temporary dam used during the casting process. There is a recess in the lower face of the upper ring to accommodate the dam. When installed, the dam is captured between the upper and lower rings. Once the RTV has set up, the lenses are separated and the dam is removed.

11.8 SHIM ATTACHMENT SURFACES

The interface between the upper and lower rings has three radial channels. The channels allow the fluid to flow easily between the inner and outer cells. This also facilitates removing air bubbles from the reservoir. The shims between the lenses need to be fixed to something to keep them from moving around. The channels also have attachment points for the shims. The shims were made from mylar shim stock of the appropriate thickness (.003" in this case).

12.0 FLUID INSTALLATION

12.1 FLUID TYPE

The fluid used in our test piece is Dow Corning 200 Fluid. This product comes in many viscosities ranging from 1 centistoke (the same as room temperature water) up to 100,000 centistokes. Fearing that we would have difficulty removing bubbles from higher viscosity fluids, we originally intended to use 1 centistoke fluid. During the filling process, 1000 centistoke fluid was accidently installed. This proved to be no problem, however, as we were able to remove all air bubbles. The 1000 centistoke fluid is the only type we have actually tried.

12.2 INSERTION

Insertion was done through one of the bleed valves. A tube is slipped over the end of the bleed valve and the fluid is allowed to flow into the cell. Care must be taken to not allow the fluid to escape as it will easily migrate to the optical surface.

12.3 AIR BLEEDING

The original design called for the fluid to enter at one of the bleed valves and the air to escape from the other. In practice, it was found that quite a bit of air was captured within the metal bellow of the volume compensator. We made a threaded hole in the end of the bellows and used the bellows itself for a bleed valve. This flushed most of the bubbles out through there. There was no need for the second bleed valve and we intend to omit it on the final design. A technique for purging the last of the bubbles was to expand the bellows by pulling on it, thus expanding the volume. Then, the end of the bellows is loosely plugged and the bellows allowed to relax to its normal length.The excess fluid is captured on its way out and the plug is tightened.

12.4 REMOVING BUBBLES

As a general rule, it is good design to provide as smooth a surface as possible so that bubbles have few opportunities to become trapped in internal features. As it was, we experienced bubbles migrating through the cell for nearly a week after the initial filling. We positioned the cell so that the bubbles migrated toward the bellows where they could be purged in the manner described above.

13.0 EFFECTS ON LENS COATING PROCEDURES

At the time of this writing, we have not yet experimented with coatings. We are currently planning to coat the outer lens surfaces with solgel. Casting the RTV requires a great deal of handling of the lenses which would no doubt ruin a solgel coating. For this reason, we are thinking of coating the lenses after they have been cast into their rings. The solgelling process would make it difficult to dip the lenses with their rings attached. Although the spinning technique has been used extensively for small lenses, it has never been done for lenses of this size. Still, we may try to spin these lenses by controlling the drying speed. Further study and experimentation will be needed.

14.0 RESULTS AND CONCLUSIONS

The test cell has been completed for several weeks and no signs of leaks or couplant migration has been noticed. The techniques and tooling developed during the experimental stage has allowed us to refine the casting process to the point where we can make a very neat and accurate installation. We have not yet developed a practical means of testing the accuracy of our calculations for the decentering and athermalization. We calculated a decentering of .00010" to .00015" which is very difficult to measure. The strains induced by thermal changes should be zero.

15.0 REFERENCES

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16.0 ACKNOWLEDGMENTS

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