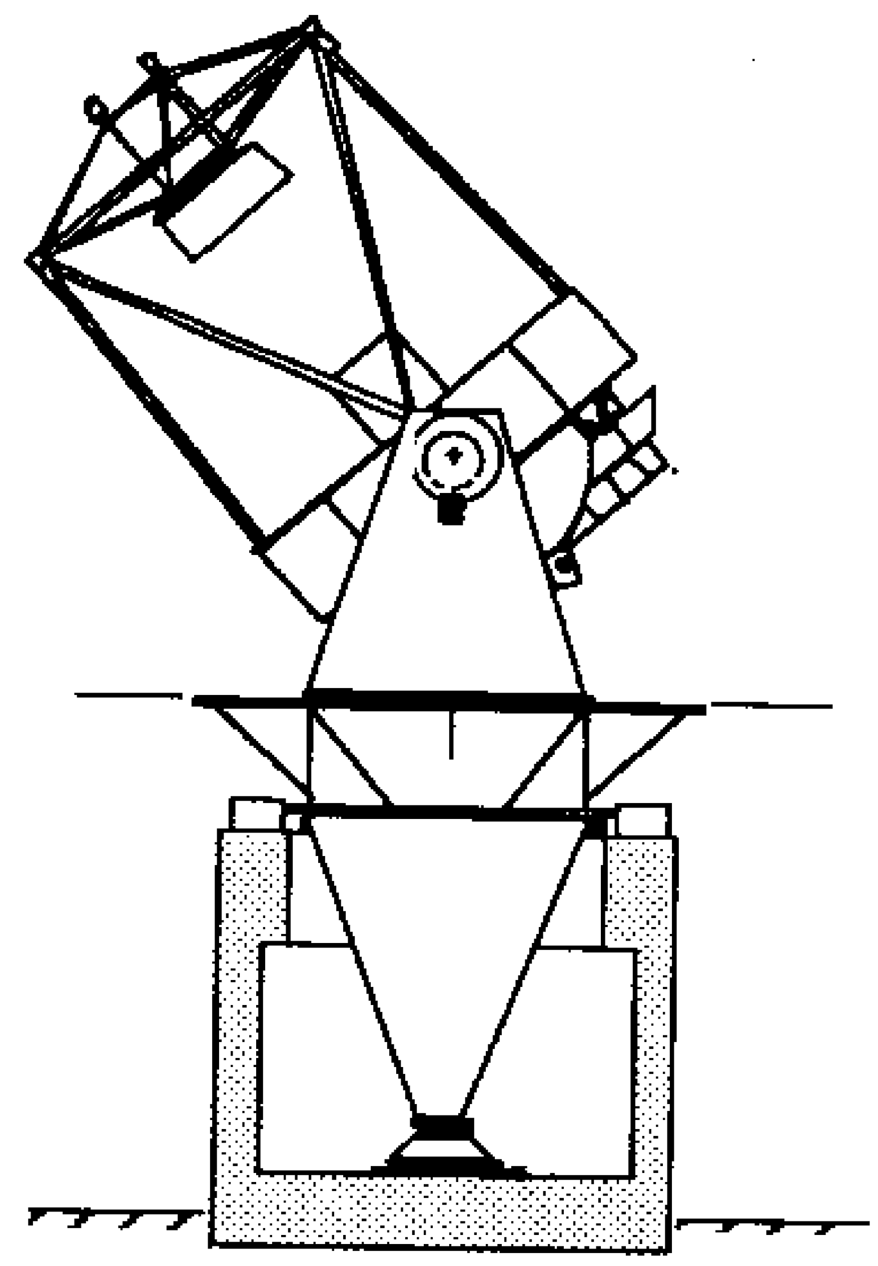
Wisconsin
Indiana
Yale
NOAO



3.5 Meter Telescope

Development of an Athermal Central Support Hub for the WIYN Secondary Mirror.

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Development of an athermal central support hub for the WIYN secondary mirror.

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The support interface for the WIYN secondary mirror calls for a metal hub to be bonded into a central cavity in the light weight mirror blank. In service the telescope can be subjected to temperature variations from 100° to 0° F. Over this temperature range significant stresses can develop in the glass due to the different thermal expansion coefficients of the glass, the metal, and the adhesive. Other characteristics of the adhesive also influence the glass stress levels. A finite elements model was built to study this problem and several arrangements were analyzed. The study yielded a design for a mounting hub which is athermal in the sense that it does not induce any significant stress in the glass with changing temperature.

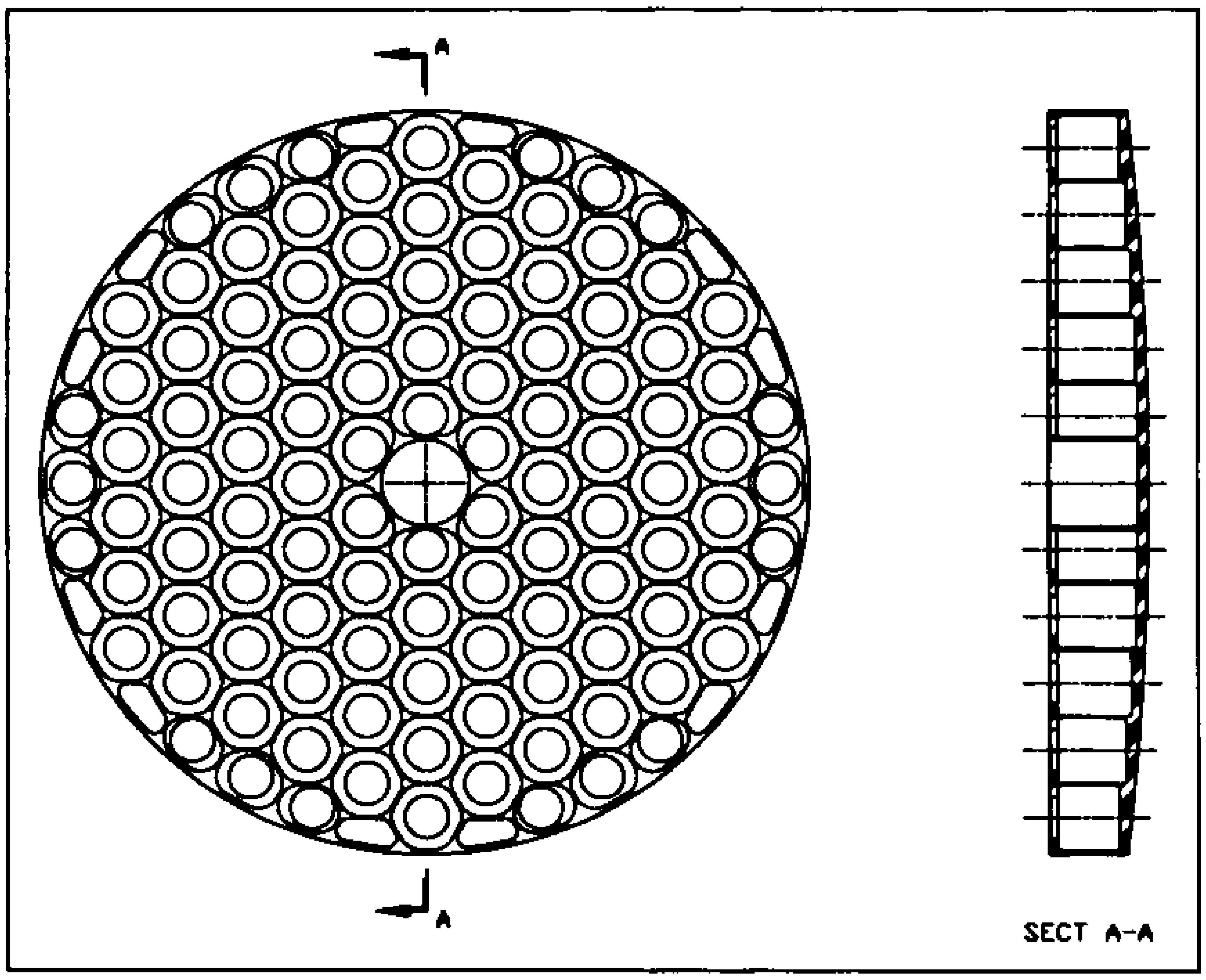

Figure 1: The WIYN secondary mirror blank.

The model

The WIYN secondary mirror blank is made of Zerodur in a lightweight honeycomb structure produced by machining a solid glass billet. It is 48" (1.2 m) in diameter, plano-convex in shape, and 6" thick at the center. Approximately 72% of the solid weight is removed leaving a blank weight of about 250 lbs. The mirror blank is shown in figure 1.

A finite elements model (FEM) was built to simulate a portion of the mirror blank. One quadrant of the central region was modeled including part of the mounting hub and glue bond. The model also included the holes in the back of the mirror blank. Figures 2 and 3 show quartering views of the model.

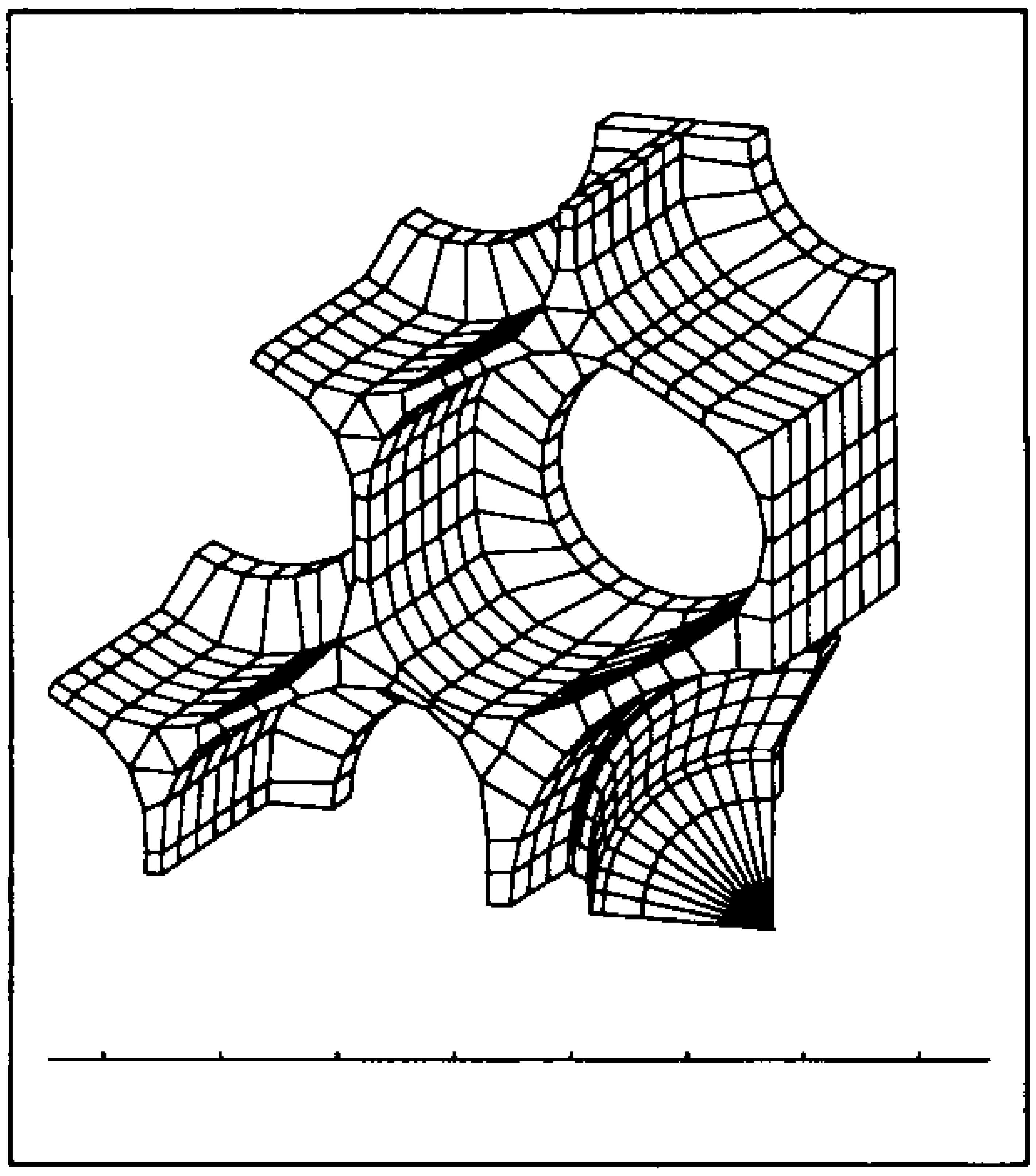

Figure 2: Quartering view of the FEM from "inside".

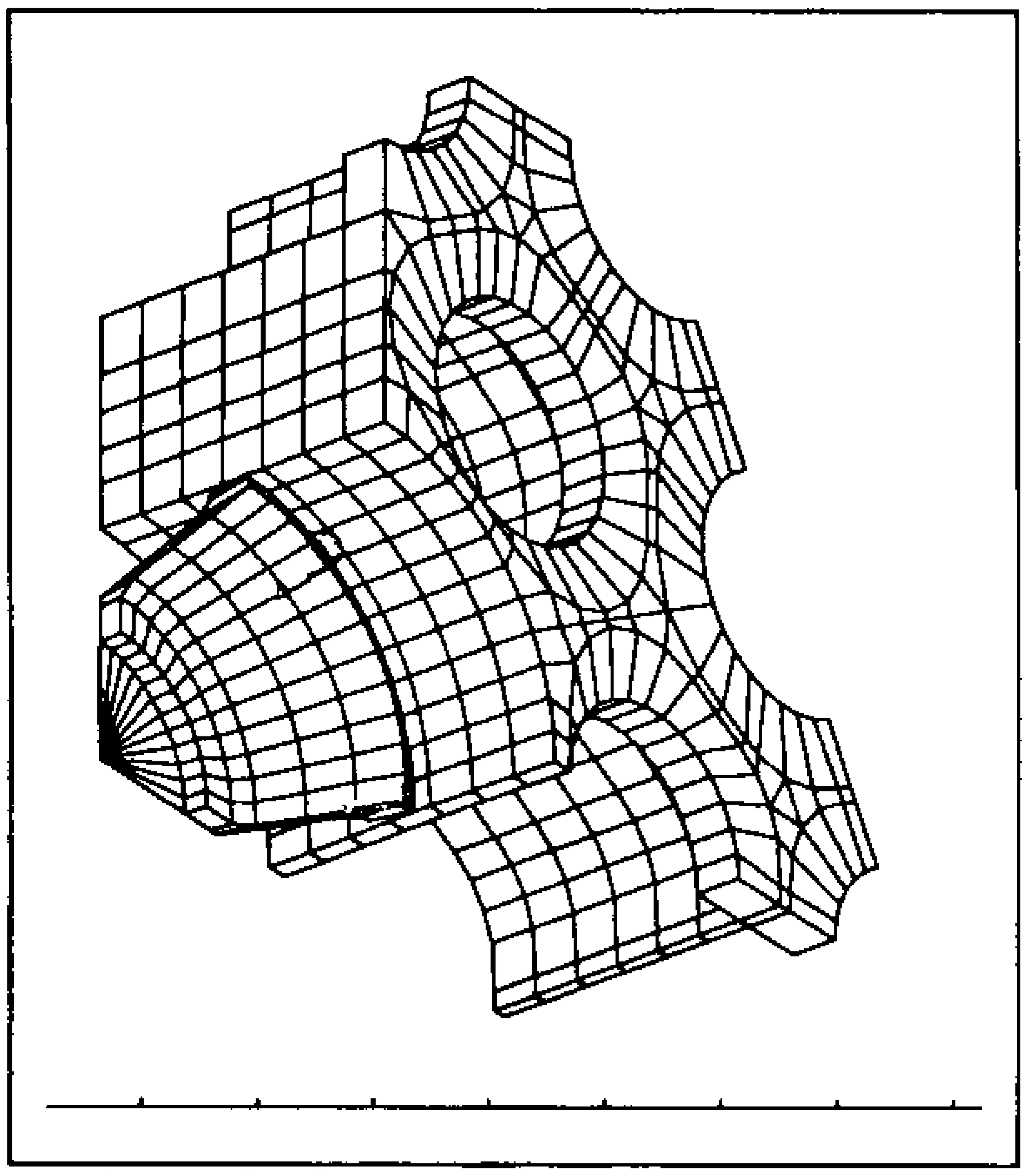

Figure 3: Quartering view of the FEM from the back.

Forces induced by a temperature change result in a radially symmetric load pattern, hence symmetrical boundary conditions were used to simulate the full mirror. The design of the mirror mount decouples the hub from axial forces, but the full mirror weight is supported by the hub in the lateral direction with the telescope at horizon pointing. Gravity induced forces result in an anti-symmetric load pattern. An appropriate combination of symmetrical and anti-symmetrical boundary conditions were used for this load case. Strictly speaking, the boundary conditions modeled a structure with holes through both the back and front plates. This made the FEM somewhat weaker than the true mirror blank.

Apart from this, the model faithfully represents the central region of the mirror blank including the central core, the first ring of six hexagonal cells, and half of each of the second ring of 12 hexagonal cells. Stresses in the outermost elements of the model approached zero in every load condition indicating the model was large enough to accurately predict the local thermal and gravity induced stresses.

The model was built using GIFTS "SLD8" solid elements. These are first order, isoparametric solid brick elements consisting of eight points with three degrees of freedom at each point. A total of 1963 points were used to generate 576 brick elements.
The GIFTS finite elements program calculates elements stresses in global coordinates or the principal stresses $\sigma 11$, $\sigma 22$, $\sigma 33$ and τmax along with direction cosines to orient the plane of maximum principal stress. The maximum principal stresses are of most interest and were recorded for each FEA run.

Each version of the model contained three materials; Zerodur, Invar, and either Milbond or Flexane adhesive. The materials properties are listed in table 1.

Table 1) Materials properties

	Material	Young's Modulus (psi)	Poisson Ratio	Shear Modulus (psi)	Yield Stress (psi)	Mass Density (lb/in^3)	Thermal Expansion (in/in/°F)
Glass	Zerodur	1.36E+07	0.24	5.484E+06	725	0.0912	0.0
Hub	Invar	2.14E+07	0.33	8.045E+06	75000	0.2898	7.5E-07
Glue	Milbond	4.10E+04	0.41	1.464E+04	2099	0.0413	6.2E-05
Glue	Flexane	4.00E+03	0.41	1.333E+03	500	0.0379	1.1E-04

For elastomer materials E is non-linear and is usually specified at some percentage of elongation such as 100% ($d=L$) and 500% ($d=5L$). Unfortunately, GIFTS does not support non-linear materials. Instead, the elastomers were treated as linear over the small elongations ($d/L<10\%$) encountered in these load cases.

Adhesives properties

Two adhesives were chosen as candidates for bonding the insert; *Milbond,* an epoxy adhesive, and *Flexane*, a polyurethane adhesive (both are trade names). Milbond is made to military specifications and is expressly formulated for bonding optical glass to metal for service in severe conditions. It is available in either a two part epoxy, or can be used with an additional primer which also consists of two parts making a four part kit. Use of the primer decreases cure time from 7 days at room temperature to about three hours. Associated products are also available: a Milbond separation coating which prevents the epoxy from adhering to a coated surface (to protect areas from epoxy contamination), and *Milsolve*, a decementing agent which can be used to separate the epoxied pieces.

Flexane is an industrial urethane product used for a number of applications such as forming "rubber" drive tires, metal forming dies, and for repair or replacement of rubber parts. It is formulated to reduce visco-elastic flow. Flexane comes in two parts, a urethane resin and a curing agent. These are mixed together similar to a two part epoxy. Cure time is seven days. Norm Cole reports he has used Flexane quite successfully for several mirrors with similar central support hubs.

The range of operating temperature for the WIYN telescope is 0° to 100° F. Both adhesives are formulated to set at room temperature or above, thus the largest anticipated thermally induced stresses will develop when a part which was bonded at 70° F is subjected to a 0° F ambient temperature. At these temperatures Milbond epoxy becomes brittle, in other words, the elastic modulus E increases as temperature decreases. The temperature dependency of E has been measured for Milbond and this data is available from the distributor. This data was interpolated to obtain a value for E at 0° F.

The elastic modulus of urethanes is rumored to be less dependent on temperature, but data was not available from the manufacturers. Instead, the temperature dependence of E for Flexane was experimentally determined. Elastic modulus is usually determined by tensile tests. A sample of the material is subjected to a tensile load, its elongation is measured, and the modulus is determined from:

$$E = \frac{P\,L}{A\,d} \qquad (1)$$

where: P is the load
L is the unloaded length
A is the unloaded cross sectional area
d is the deflection under load

The intent of this test was to detect a change in E with temperature. The test was arranged so that P was constant, and L and A were very nearly constant with respect to temperature. Under these conditions, a change in E can be found from:

$$\frac{E_{T1}}{E_{T2}} = \frac{d_{T2}}{d_{T1}} \qquad (2)$$

This form of test is very convenient, since only one quantity, d, need be measured. Samples can be used without particular attention to dimensional control.

Three samples of Flexane were tested. One end of each sample was clamped and a weight was suspended from the other end. The deflected and undeflected lengths were measured between two marks on the samples. These measurements were repeated three times for each sample with the samples at room temperature. The samples were then chilled to 5 °F and the deflected and undeflected lengths were measured as before. Test data is included in appendix A.

The test results indicate that for Flexane the change in *E* with respect to temperature is 6.3 +/- 19.7% over a 75° F temperature change from 80° to 5° F. This is not a significant change.

Discussion of FEA results

The initial FEM incorporated a preliminary design of the central hub. This is shown in figure 4. The preliminary hub design supports the glass at two annular glue bonds near the front and back of the mirror blank, a configuration chosen to reduce gravity induced stress in the glass. The hub has a tapered waist which weighs about 12% less than a similar design with a straight cylindrical waist. The tapered hub walls were 0.09" thick, and the piece weighs 3.7 lbs.

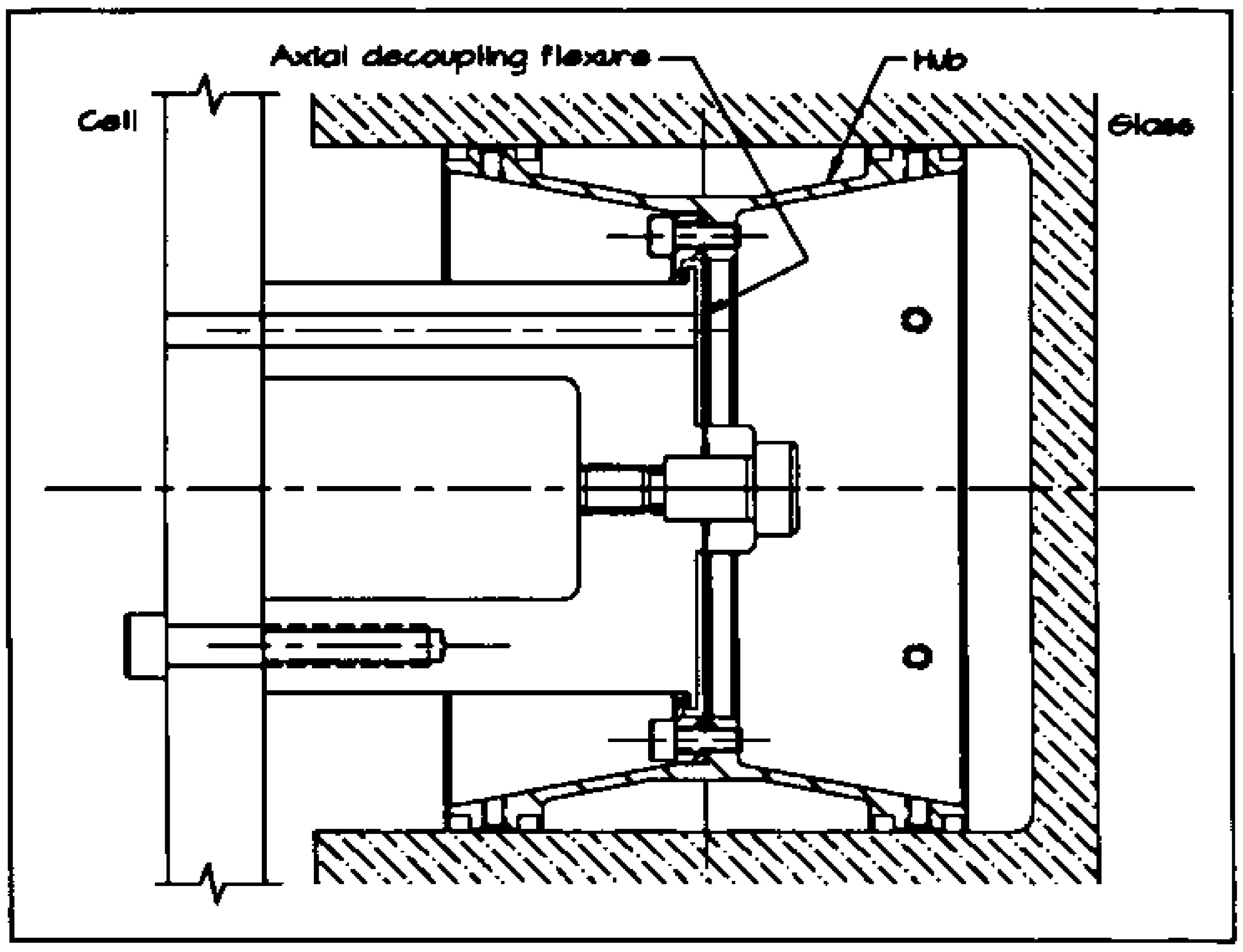

Figure 4: Preliminary central hub design.

Various runs were done using this model and variations on the central hub area of the model. A summary of the results is presented in Table 2.

Table 2) Maximum principal stresses in glass for various hub geometries and adhesives.

Hub Geometry	Load Case	Adhesive	Tension (psi)	Compression (psi)	Shear (psi)	Deflection (inches)
Solid	Thermal	Milbond	138.4	-563.8	312.4	--
Six slots	Thermal	Milbond	112.1	-310.6	201.0	--
Six slots, .06" wall	Thermal	Milbond	111.0	-269.4	181.8	--
Twelve slots	Thermal	Milbond	110.5	-305.5	195.5	--
Twelve slots, .06" wall	Thermal	Milbond	110.7	-269.4	201.0	--
Solid	Thermal	Flexane	83.3	-242.5	130.6	--
Six slots	Thermal	Flexane	67.5	-133.6	84.0	--
Athermal hub A	Thermal	Flexane	27.8	-20.8	17.9	--
Athermal Hub A	Gravity	Flexane	38.7	-38.7	21.5	0.00094
Athermal hub B	Thermal	Flexane	1.3	-2.5	1.2	--
Athermal hub B	Gravity	Flexane	52.1	-52.1	23.6	0.00263
Athermal hub B	Thermal	Milbond	12.3	-22.7	12.9	--
Athermal hub B	Gravity	Milbond	64.5	-64.5	29.0	0.00084

The model was run using the two adhesives. When both adhesives resulted in fairly large stresses in the glass, several more runs were done each with alterations to the geometry of the central mounting hub. Six, and then twelve slots were added to the model of the hub to allow radial compliance. While slots reduced the thermal induced stress, the remaining stress levels were still high. The thickness of the mounting hub walls was reduced from 0.09" to 0.063". Each alteration reduced stress but still did not achieve the 100 psi design goal.

Next an athermal design was tried. The preliminary athermal design (athermal hub A in table 2) used "H" shapes inserts to span between the glass and the central cylinder. This allows two glue bonds between the glass and central cylinder. These glue bonds are situated to offset one another exactly canceling the glue thermal expansion. The FEA results indicate the effectiveness of the design both for thermal and gravity loading.

This preliminary athermal design presented some difficulties for fabrication, so further FEA runs were done to simplify the design. The final design (athermal hub B in table 2) is shown in figure 5. The inserts were changed from "H" shaped to "wishbone" shaped, which is easier to fabricate and install. The contact area of the glue bond has been reduced to slightly less than half that in the initial design. Limiting the contact area raised the glass stresses induced by gravity loads, but these remained acceptably low.

In addition, a more detailed analysis was done to further optimize the design. A small difference in the thickness of the two glue bonds can compensate for the slight difference in expansion between the Zerodur and the invar. The glue thicknesses can be found by solving the equation:

$$(a+c)\ \alpha_{metal} = (b-d)\ \alpha_{glue} \tag{3}$$

where: *a,b,c, & d* are dimensions according to figure 5
α is the coefficient of thermal expansion

This equation suggests that metals other than invar could be used; however the geometry is inconvenient. For example, in order to use a moderately low expansion stainless steel ($\alpha = 9.6 \times 10^{-6}$ in/in/°F), the difference in glue bond thickness (*b-d*) would have to be about 1/4". With invar and Flexane the optimum difference in glue bond thickness is 0.020", and the thermally induced stresses in the glass are reduced to negligible levels as shown in table 2.

Stress Criteria

There does not seem to be a general consensus on a safe allowable stress limit for glass. Different groups work to different criteria.

Experiments done by Schott Glass Technologies indicate that the strength of Zerodur is a function of its surface finish. Samples of Zerodur with surfaces finished by grinding with various mesh grits from D15A (12.5 / 15 micron grit) to D251 (US Mesh 60/70 per inch per ASTM E 11) were tested to failure in bending. From the Schott results it appears that the strength of rough

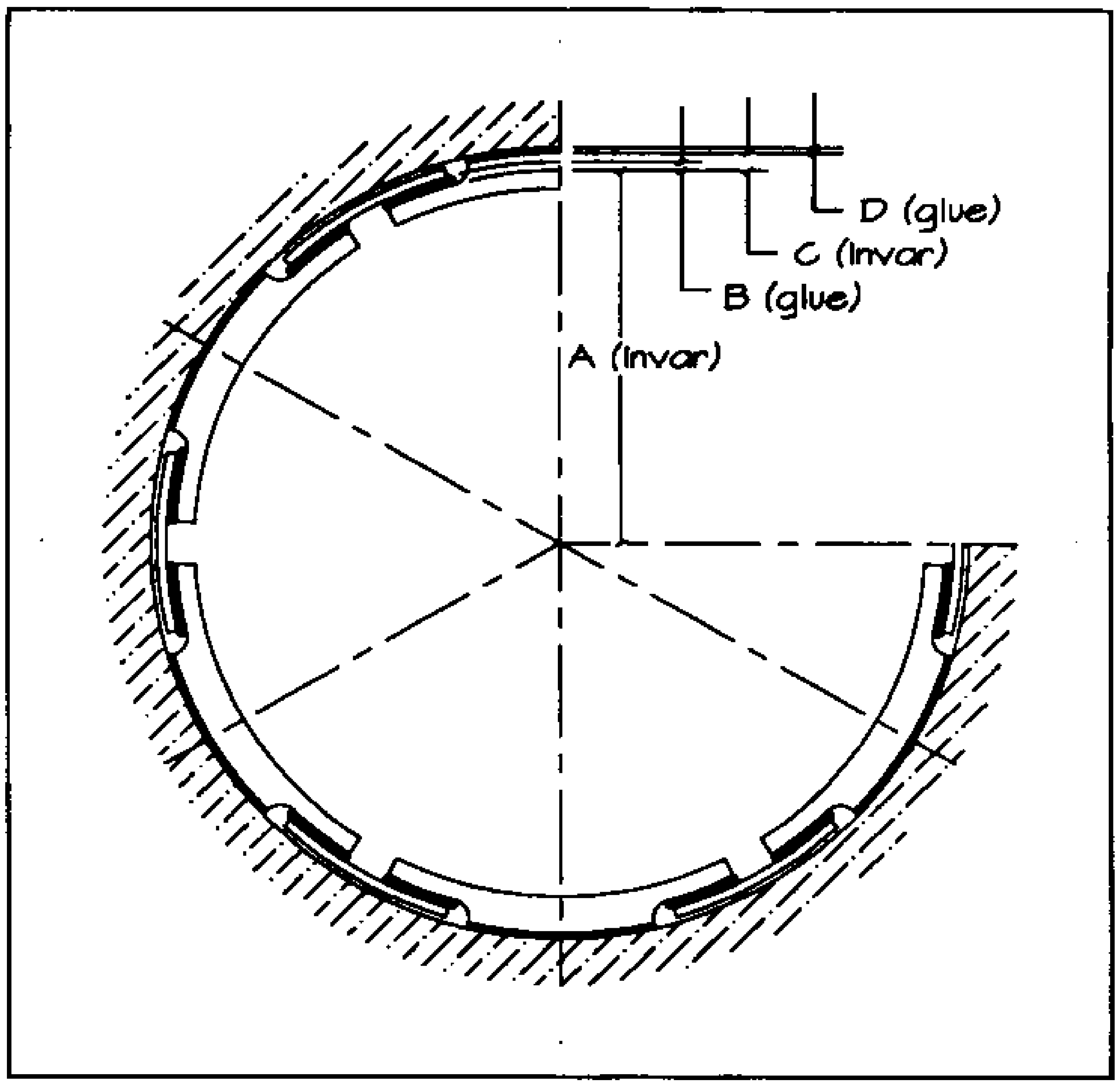

Figure 5: Athermal hub design (B).

ground Zerodur approaches a limiting value of about 40 MPa (5,800 psi). Schott recommends a design stress limit of 725 psi for Zerodur, which implies a safety factor 8.

Corning Glass recommends a design limit of 7 MPa (1015 psi) for silica; in contrast the Steward Observatory Mirror Lab has adopted a design goal of 100 psi for Ohara E-6 (borosilicate) glass.

Analysis of the stresses at the support interfaces of the 3.5m borosilicate primary mirror (Woon-Yin Wong, 1990) indicate that the primary mirror is commonly subjected to gravity induced stresses of 182 psi in tension and (-)466 psi in compression when resting on three points.

For the WIYN secondary we adopt the 725 psi limit suggested by Schott as a design *requirement*, and at the same time adopt the 100 psi limit as a design *goal* wherever this can be achieved with a reasonable design.

Conclusion

All of the center hub mounts meet the design requirements for stress; only the athermal hub design meets the design goal. Since this design is reasonable to fabricate and install it has been selected for the WIYN secondary.

TEST OF FLEXANE 80® URETHANE ADHESIVE

DEPENDENCE OF ELASTIC MODULUS ON TEMPERATURE

$$d = \frac{PL}{AE} = C/E$$

$$\frac{d_1}{d_2} = \frac{E_2}{E_1}$$

LENGTH MEASURED WITH DIAL CALIPER

TEMPERATURE WITH A THERMOMETER

TEST SAMPLE #1 : .34" × .045"   W = 3.4 lbs

T	UNWEIGHTED	WEIGHTED	ΔL	
80 °F	1.100	1.220	.120	ELONGATION = 11.%
"	1.100	1.230	.130	
"	1.110	1.225	.115	
AVG →	1.103	1.225		AVG DIFFERENCE = .122
5 °F	1.115	1.225	.110	
	1.105	1.220	.115	
	1.100	1.230	.130	
AVG →	1.107	1.225		AVG DIFFERENCE = .118

TEST SAMPLE #2 .22" × .025"   W = 2.4 lbs

T	UNWEIGHTED	WEIGHTED	ΔL	
80 °F	1.735	2.100	.365	ELONGATION = 21%
"	1.755	2.115	.360	
"	1.750	2.135	.385	
AVG →	1.747	2.117		AVG DIFFERENCE = .370
6 °F	1.735	2.140	.405	
	1.755	2.120	.365	
	1.750	2.150	.400	
	1.747	2.137		AVG DIFFERENCE = .390

TEST SAMPLE #3 .30 × .026"   W = .8 lb

T	UNWEIGHTED	WEIGHTED	ΔL	
78 °F	1.345	1.425	.080	ELONGATION = 5%
"	1.365	1.420	.055	
"	1.365	1.420	.055	
AVG	1.358	1.422		AVG DIFFERENCE = .064
5°	1.345	1.400	.055	
	1.345	1.390	.045	
	1.335	1.395	.060	
AVG	1.342	1.395		AVG DIFFERENCE = .053

MAXIMUM VARIATION IN MEASUREMENTS = .03"