Manufacture of a 2-m mirror with glass membrane facesheet and active rigid support

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ABSTRACT

A 2-m diameter mirror is being manufactured as a demonstrations for NASA's Next Generation Space Telescope (NGST). This mirror meets the challenging requirements of cryogenic operation and very low mass using an active control system. The mirror system consists of an aluminized glass membrane, 2 mm thick. This membrane is supported and controlled based on wavefront measurements with 169 remotely driven actuators. The system rigidity is provided by a lightweight carbon fiber composite structure. This entire mirror system, 2 meters across weighs less than 40 kg, and will demonstrate 20 nm surface quality in a cryogenic test facility at 35 K.

Keywords: space optics, lightweight mirrors, active optics

1. INTRODUCTION

The approach to making space optics using thin glass facesheets with active rigid support draws directly on the enormous technology heritage for glass telescope mirrors. In the past 50 years since the 5-m, $f/3.3$ mirror was made for Palomar, diameters have increased to 8 meters. The reduction in focal ratio has been more dramatic, first to $f/1.8$ and now to $f/1.14$ for the two 8.4 m mirrors being made by the University of Arizona for the Large Binocular Telescope. These far more aspheric surfaces also are much more accurate, reaching the optical diffraction limit. Mass densities for ground mirror systems have not reduced much over time, but this does not reflect any technological limit. There is little advantage in performance and cost of ground based telescopes for densities much less than 1000 kg/m^2 including the steel cell that holds the mirror.

The need for lighter mirrors in space led to the development of lighter weight glass technologies. Honeycomb structures of ~200 kg/m^2 were used in the 11 ton Hubble Space Telescope and more recently glass shells 17 mm thick (37 kg/m^2) have been developed for a flyable 4 m mirror weighing 440 kg. Such shells were stiff enough to allow support by traditional actuators that control the force applied to the glass.

For the still lighter mirrors, thinner glass shells are sufficiently flexible that the traditional flotation (force actuated) support is no longer desirable. However, as we have demonstrated, glass membranes as thin as 2 mm can be made into high quality mirrors, provided they are attached rigidly to a stiff back-up structure. This structure need not be stable to optical tolerance, provided the actuators can be adjusted to compensate for thermal or other deformations. The advantage of making a mirror in this way is that the attributes of a smooth, polishable surface and a rigid lightweight structure are separated. The choice of materials and structural designs for each can be separately optimized, and a great reduction in density obtained. The first mirror we made in this way weighed 20 kg/m^2 in total, including the glass membrane, actuators and carbon fiber composite support. The 2-m mirror, presented here, weighs 12 kg/m^2. We also see how this technology can reach 5 kg/m^2 with current materials and fabrication technologies.

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2. DESIGN CONCEPT

Traditionally, mirrors for space use glass blanks that are sufficiently massive to hold their own shape under polishing, launch, and for final operation. The Hubble Space Telescope solution was a mirror made as a thick, rigid, monolithic glass honeycomb sandwich, of glass with near zero coefficient of thermal expansion (CTE) at room temperature. The faceplate was thick enough and the honeycomb cells small enough so polishing forces did not deform the surface, and thermal distortion was avoided by operating the mirror at the fabrication temperature (~293K). The much lighter NGST mirror with inevitably thin sections is much more subject to deformation under gravity and stray forces, deformation under the polishing tool, deformation when cooled 250° C to the operating temperature because of CTE variations, and deformation because of large temperature gradients at the operating temperature.

We are now building an NGST Mirror System Demonstrator (NMSD) that overcomes these problem.[1] Our solution involves:

- Making the mirror surface as a membrane of glass with the highest CTE uniformity and zero CTE at the cryogenic operating temperature.
- Optical fabrication of the membrane in one piece while it is rigidly and uniformly supported in a condition of zero internal stress. In this support, we use figuring by methods already proven for large rigid mirrors.
- To correct residual errors, and to raise the resonant frequency, the membrane is linked by position actuators to a rigid ultra-lightweight structure.
- The actuators are adjusted to preserve the wavefront quality, as measured using star light, in the presence of deformation or creep in the support structure. The concept of using actuators to compensate for the motion of the support structure is shown below in Fig. 1.

The NMSD implements these concepts with a 2-mm thick glass membrane, supported by 50 actuators per sq. meter. The glass provides an excellent optical surface and will maintain its shape over scales too small to be corrected by the actuators. The actuators are remotely driven fine pitch screws that achieve 6 nm rms resolution and require no power to hold their position. The support structure is made from paper-thin laminated sheets of composite carbon fiber.

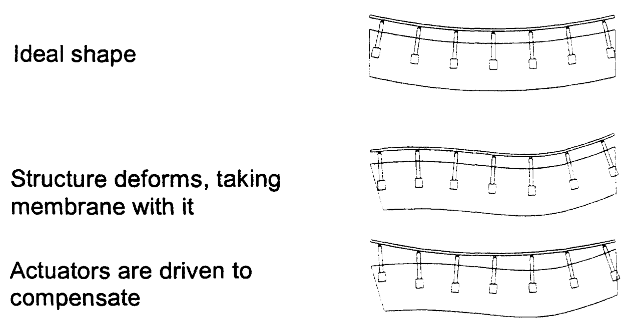

Figure 1. Use of position actuators to maintain the optical surface.

The actively controlled mirror has several important advantages over a fixed mirror. It eases requirements for thermal stability of the structure while the temperature drops hundreds of degrees and may have variations across the mirror of tens of degrees. It also accommodates changes in shape due to material instability over the life of the observatory. Also, the membrane does not have to be made accurately on large scales because it can be deformed into shape. The system is made to be fail-safe by including more actuators than are necessary. If an actuator fails, it can be disengaged and retracted from use. The loss of any one actuator, or even pairs of adjacent actuators, does not significantly affect the mirror shape. Also, the actuators require no voltage or command to hold their positions, so if the carbon fiber structure is stable for weeks, then the surface shape will not need to be adjusted for weeks. When an adjustment is required, the error in the mirror can be measured using images from a bright star and applying phase retrieval algorithms.

3. DESIGN OF 2-M NMSD

The design of the mirror uses a fixed mass budget and we optimize for surface figure, high resonant frequencies, and launch survival by allocating this mass optimally to actuators, support structure, and membrane thickness. The design of the 2-m NMSD is shown below in Fig. 2. The mass summary is given in Table 1 and the surface error budget is summarized in Fig. 3.

A basic tradeoff in the design involves the number of actuators. Ideally, the membrane will be perfectly manufactured and will require zero force to maintain its shape in space. In reality, the membrane will have strain due to the fabrication process and the variations of the material properties within the blank. These tend to warp the membrane and require corrective forces to maintain the correct shape of the membrane. The actuators apply this force at discrete locations and can cause ripple in the surface at the period of the actuators. This effect can be minimized by making the membrane thicker, thus stiffer to the local forces, or by increasing the number of actuators.

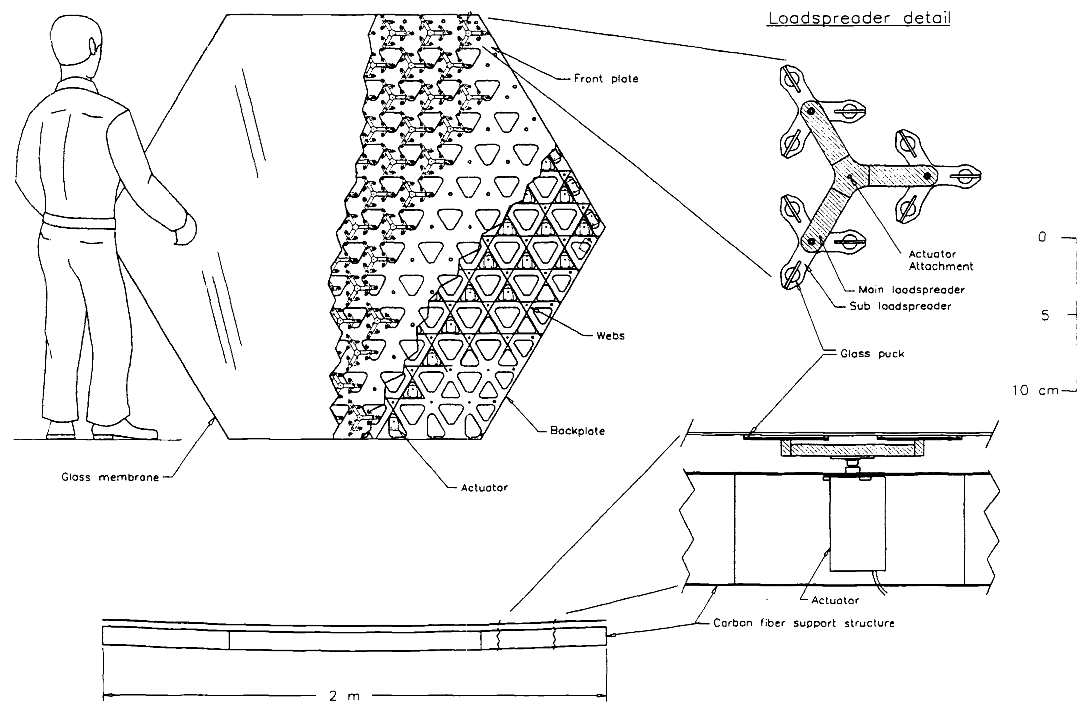

Figure 2. 2-meter NGST Mirror System Demonstrator.

Table 1. Mass budget for the 2-m NGST demonstration mirror.

Item	Kg/m^2
Glass membrane, 2 mm thick borosilicate, 2.2 gm/cm^3	4.4
Actuators and cabling, 50/m^2, 50 gm per actuator	2.5
Load spreaders, 50/m^2, 27 gm per load spreader	1.4
Attachments to membrane, 450/m^2, 0.9 gm each	0.4
Launch restraint hardware, 6.2 gm per actuator	0.3
Carbon fiber support structure	4.0
Total mass per square meter	**13.0**

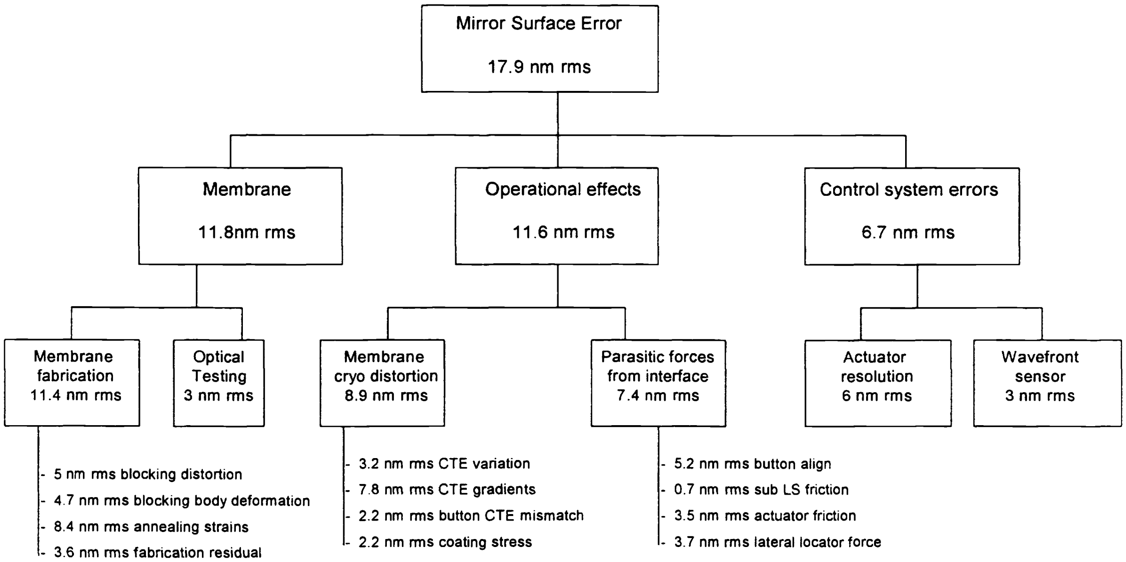

Figure 3. Error budget for the 2-m NMSD for operation at at 35 K.

We have chosen borosilicate glass for the cryogenic telescopes because of its zero CTE (coefficient of thermal expansion) at 35 K.[2] Other glasses have better performance over a wider range, but the borosilicate is best in the NGST operating range. Borosilicate glass is also obtainable at moderate cost, and it is made with excellent CTE homogeneity. Schott's Zerodur glasses also have good cryogenic performance, although standard Zerodur has demonstrated some instability between 20 and 30 K. Figure 4 shows CTE data for candidate materials.

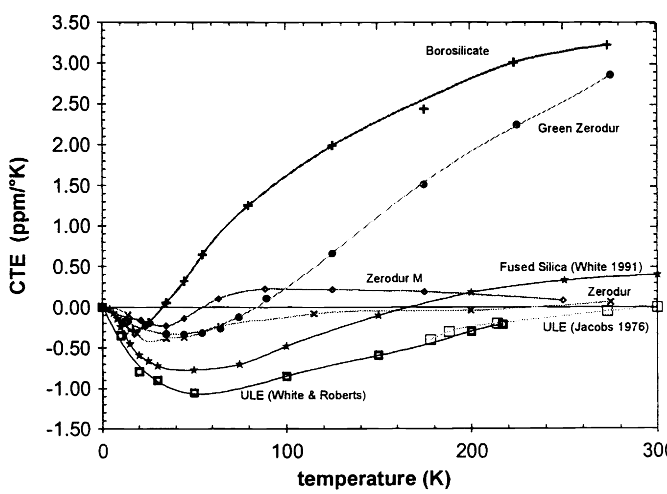

Figure 4. CTE for various glasses down to cryogenic temperatures.

Our system design uses load spreaders to distribute the load from each actuator to 9 points on the glass. This is driven by the requirement to minimize the stress concentrations at the glass attachment point during launch. The load spreaders also distribute the actuator forces to minimize the effect of the actuators on the optical figure. The glass attachment is difficult because this system must support high loads during launch and it must provide almost no load when it is operational at 35K. A diagram of the load spreader attachment is shown below in Fig. 5. We bond small glass pucks to the membrane surface to allow a rigid attachment and to minimize stress when the part is cooled.

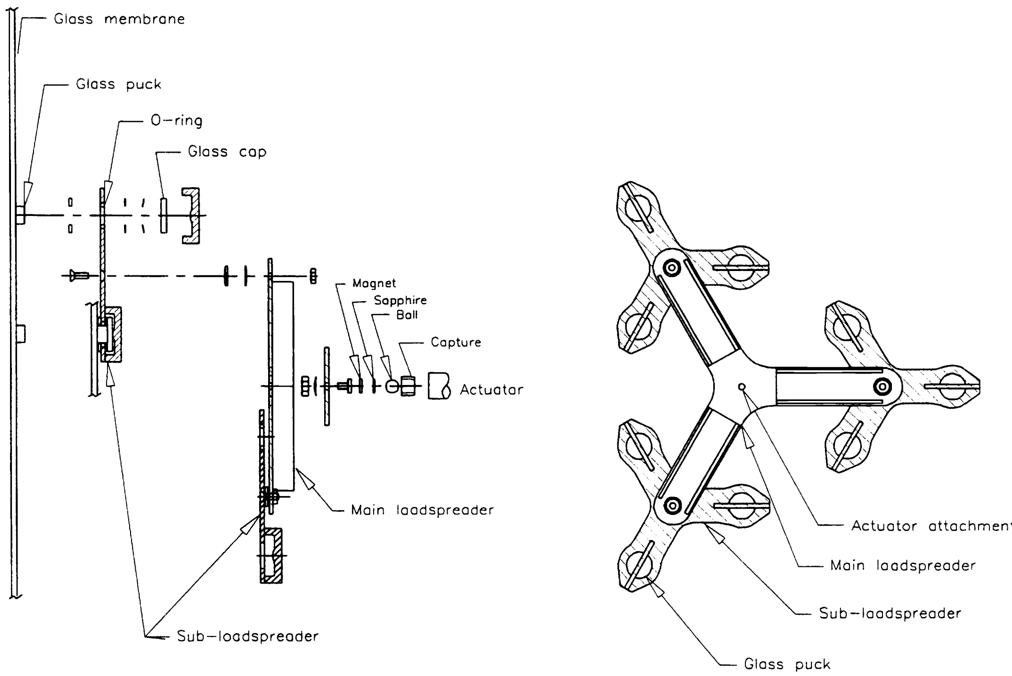

Figure 5. Exploded side view and assembly drawing showing the 9-point load spreaders and their attachment to the glass membrane.

In operation the actuators are attached to the load spreaders with a weak magnet. Since very little force is required, this allows us to control the shape. In addition, it allows actuators to break away before any force gets large enough to damage the glass or load spreaders. Parasitic lateral forces are avoided by using a ball coupling at the magnet. The actuators also have remotely controlled retraction mechanisms that can remove any actuators that malfunction. The actuator density is sufficient to maintain surface control even if 10% of the actuators fail.

The launch loads of the glass membrane are taken through the actuators. This requires an additional set of attachments that keep the magnet-ball in compression and can take lateral loads. We solved this issue using cables that are pre-tensioned before launch to pre-load the actuator, shown in Fig. 6. This system was analyzed and shown to provide a safe support for the mirror.

As the actuators retract, the cables will go slack. The membrane is then supported only by the actuators that constrain motion normal to the surface and three tangent arms that prevent lateral motion and rotation.

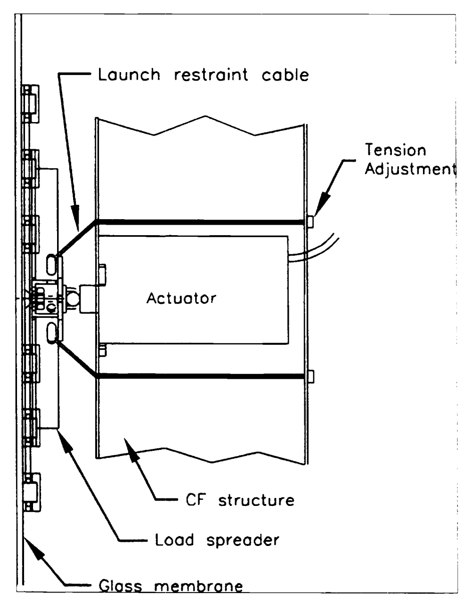

Figure 6. Side view showing launch restraint cables.

4. GLASS MEMBRANE

The technology that makes this concept feasible is the fabrication of the 2-mm thick glass membrane. At the University of Arizona, we have already developed a method of making these membranes as part of a program funded by the Air Force Office of Scientific Research.[3] We use membrane mirrors with a high density of fast actuators for compensating the atmospheric turbulence that limits ground-based telescopes. We are now fabricating a 64-cm adaptive secondary mirror for the MMT that uses a 1.6-mm facesheet supported by 330 actuators driven at 1 kHz.[4]

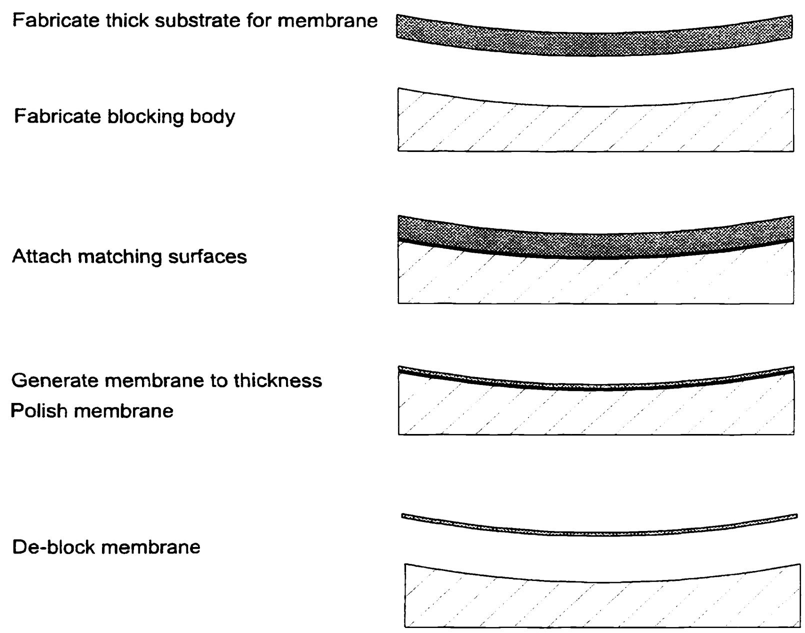

Figure 7. Concept for fabricating thin glass membranes.

Our fabrication method is designed to take advantage of the stressed lap method already proven in the figuring of large aspheric mirrors. It calls for the membrane to be "carved out" from a relatively thick disc of glass of known high quality. We start with two thick disks; one will become the membrane and the other for the stiff blocking body to which the membrane is attached during fabrication. A spherical convex surface that will become the back of the membrane is first ground and polished. The second thick substrate is prepared as a rigid blocking body, with an accurately matching concave surface. The two pieces are then warmed and bonded together with a thin layer of pitch, an ideal adhesive for this purpose because it has the stiffness required for polishing, but it relaxes during the blocking operation to provide a low-stress bond. Once rigidly attached, the upper disk is machined away, down to the desired curvature and near final thickness, then ground, polished and figured. On completion of figuring, the assembly is warmed to melt the pitch, and the membrane is removed from substrate. In this way, the manufacturing process is reduced to the well-understood process of figuring a rigid mirror, and the techniques already proven for 6.5-m diameter mirrors at the University of Arizona are directly applicable. The fabrication sequence is shown in Fig. 7.

The initial membrane for the 2-m NGST Mirror System Demonstrator was made by fusing together sheets of Schott's Borofloat glass. This glass was readily available in 2-m sizes, but only 11 mm thick. To make a thicker blank, we fused 4 sheets together and slumped them to the correct curvature. Unfortunately, the fusing of these sheets was not complete and this left numerous gaps between the sheets. The stacking and the final fused substrate are shown below. These flaws proved to be critical, as we suffered numerous small fractures when we worked the glass near these areas where the fusing had not occurred properly.

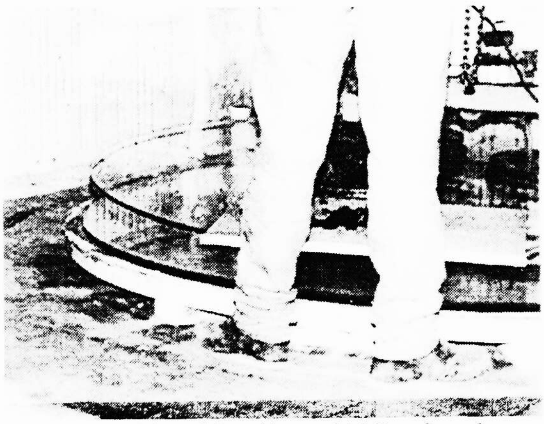

Figure 8. Stacking of four 11 mm thick Borofloat sheets prior to casting.

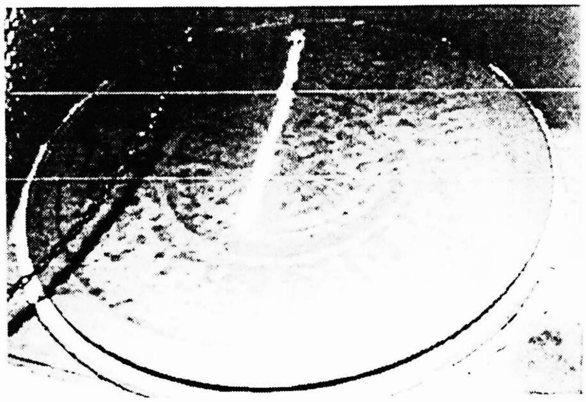

Figure 9. Final blank from 4 fused sheets of Borofloat. The dark patches are regions where the glass did not fuse.

We continued to process this membrane as an engineering test. The convex surface was ground and polished, then the part was blocked to a 10 cm thick borosilicate blocking body that had the mating convex surface. In order to avoid stressing the glass during blocking, the part was held from a whiffle tree and we controlled the force from the blocking body using hydraulic actuators. The concave surface of the membrane substrate was also filled with pitch to avoid hydrostatic buoyant forces that would distort the glass.

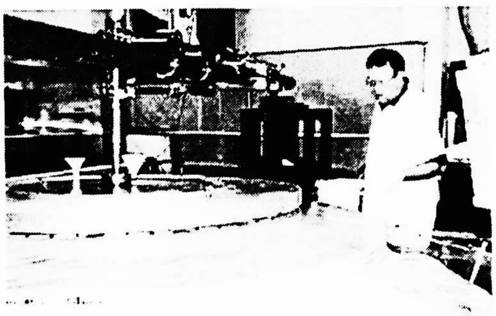

Figure 10. Grinding of convex surface of membrane substrate.

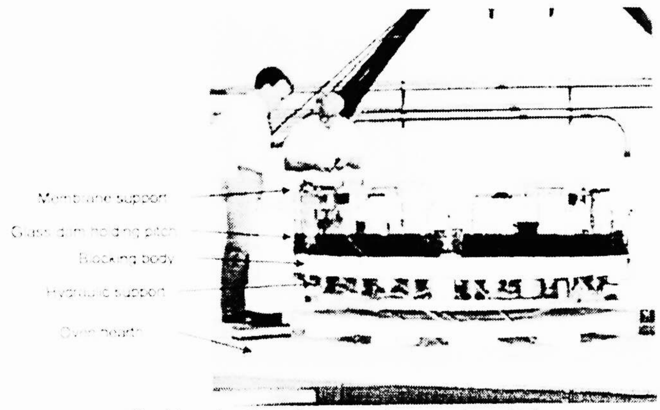

Figure 11. Blocking the Borofloat membrane using pitch

After blocking, we generated the glass down to 3 mm total thickness. This process caused numerous small fractures where the edges of the voids causes stress concentrations. We then ground and polished the optical surface to about 1 λ. After attempting to bond the fractures, we cut the membrane into its final hexagon shape while it was still blocked down. This was done using a diamond saw. We planned to de-block the membrane using a vacuum lifting tool. We performed a successful test of this de-blocking method on a 50 cm prototype. The attempt to de-block the 2-m membrane was not successful. The fractures in this glass severely limited the strength to a level that caused it to break in multiple places when we melted the blocking pitch and applied the lifting force.

Figure 12. Final polished optical surface on the Borofloat glass, as it was blocked down.

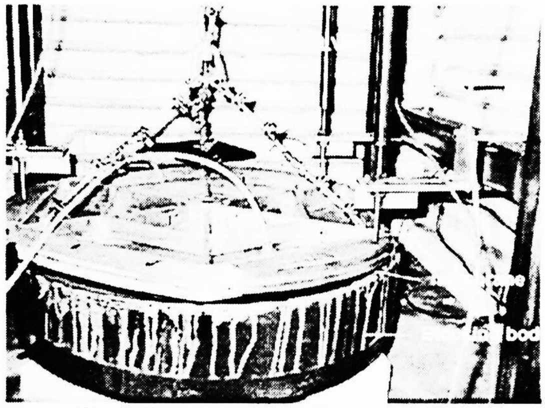

Figure 13. Deblocking test on a 50 cm substrate.

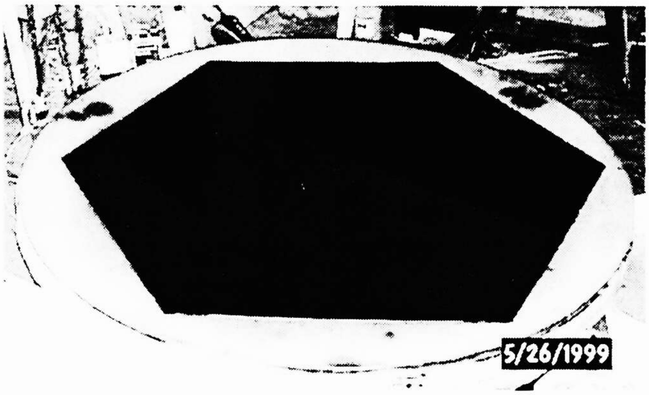

Figure 14. Borofloat membrane, cut hexagonal, still held to the blocking body with pitch.

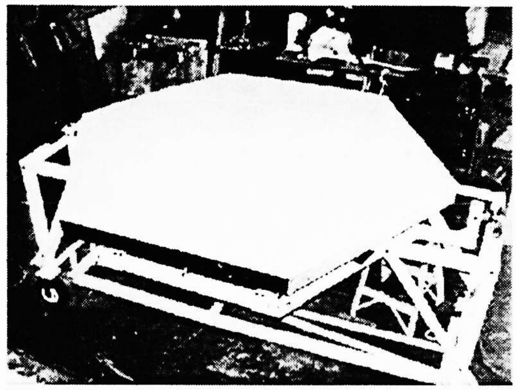

Figure 15. Deblocking tool for the 2-m membrane..

Upon discovering the fractures in the first membrane, we cast a second membrane from Ohara's E6 borosilicate glass using the 8-m rotating furnace at the Mirror Lab. This casting achieves high homogeneity because it started from a complete block of glass made in a single pot. It was then melted and flowed out to a 2.2-m blank. This initial block is shown below. We are now in the process of working the convex surface

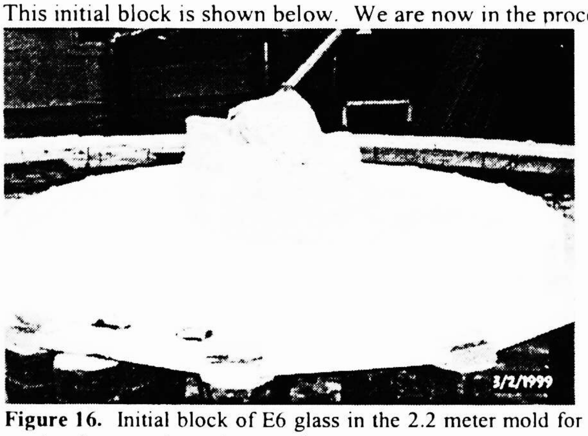

Figure 16. Initial block of E6 glass in the 2.2 meter mold for casting the second membrane substrate.

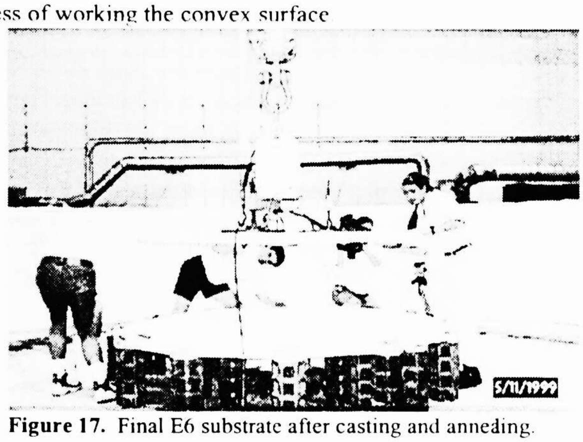

Figure 17. Final E6 substrate after casting and anneding.

5. COMPOSITE SUPPORT STRUCTURE

The support structure for this mirror was designed by the University of Arizona and Lockheed Martin and was fabricated by Composite Optics, Inc in San Diego. This structure uses a sandwich construction of carbon fiber reinforced polymer with 0.75 mm thick facesheet, 0.5 mm thick backsheet and 0.375 mm thick ribs with 150 mm spacing.

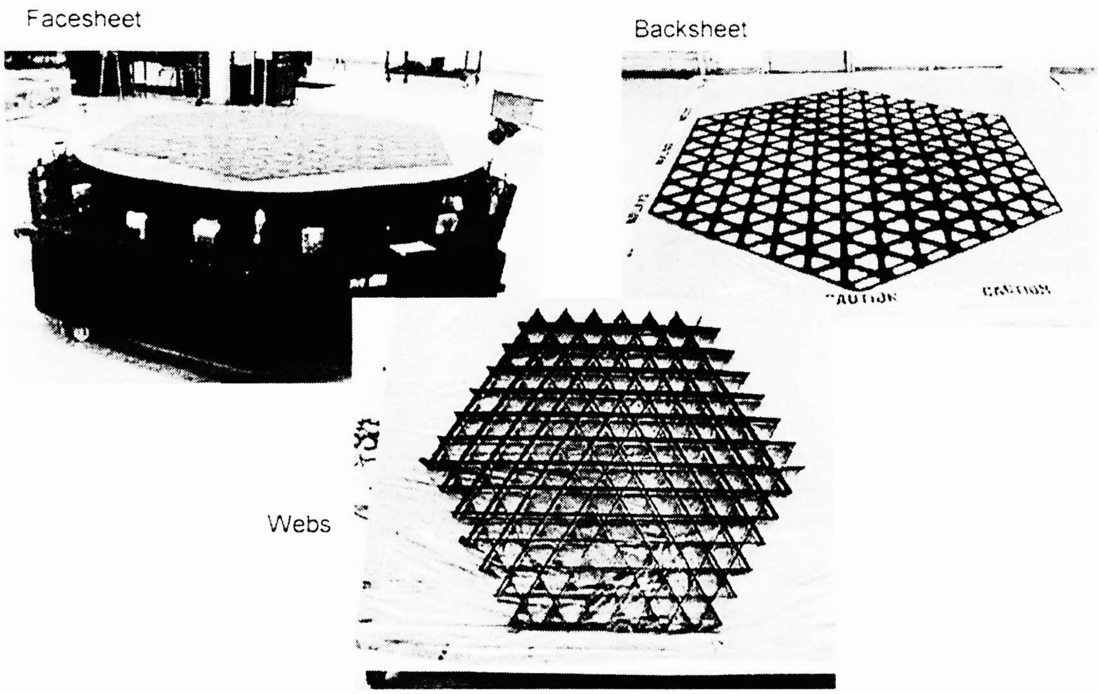

Figure 18. Components for the composite support structure at COI

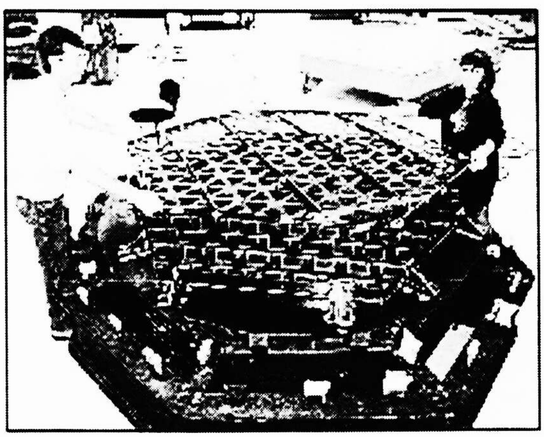

Figure 19. Assembly of the support structure at COI

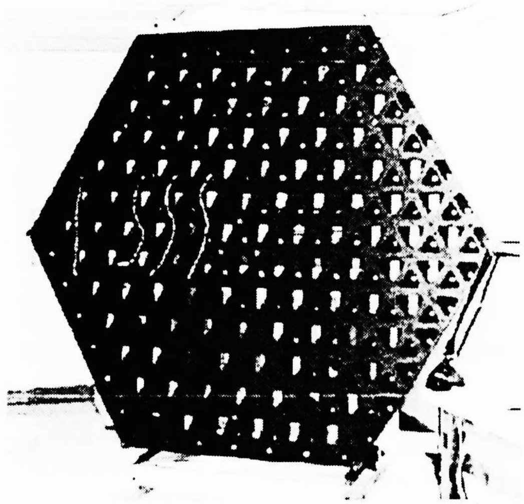

Figure 20. Final support structure with some of the actuators installed.

6. ACTUATORS AND CONTROL ELECTRONICS

A key development has been a new type of actuator to be used in the 2-m NMSD. Brian Cuerden and Roger Angel of the University of Arizona have invented and demonstrated a linear position actuator that operates equally well at ambient and cryogenic operation. The linear motion is provided by a threaded shaft stepped through a nut by an impact mechanism. This actuator has now been demonstrated with mass as low as 7 grams per actuator, to make steps as small as 5 nm at ambient and cryogenic temperatures, with total range limited only by the screw length.

In detail, the nut is held in a neutral position by flexures and can be struck by one of two electromagnetically accelerated masses that turn it momentarily to the left or right. At the moment of impact the nut accelerates rapidly and the shaft slips, because friction is not strong enough to overcome its inertia. Subsequently, as the neutral position of the nut is restored by the flexures the shaft no longer slips, since the restoring moment causes relatively weak acceleration. The net result of each impact is thus to advance (or retract) the shaft by a small amount. Correct operation requires the right balance between inertia, friction and impulse. In practice we find the device quite robust; because the acceleration of the hardened nut on impact is very high, operation is reliable for wide variations in shaft inertia and friction.

A 43 gram prototype with an inch-long ¼ - 80 thread advances between 10 and 100 nm on each impact, depending on the electrical pulse length applied to the electromagnet. It works well at both room temperature and at cryogenic temperatures. The stalling force is about 20 N. In addition, an early prototype of a smaller actuator weighing only 7 grams was demonstrated to work reliably, making steps as small as 5 nm. These actuators and data are shown below.

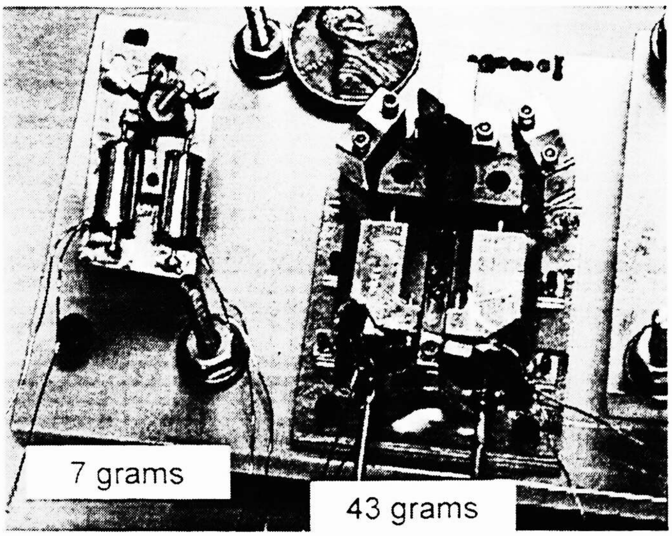

Figure 21. Prototype actuators. The 43 gram actuator was demonstrated at 77 K.

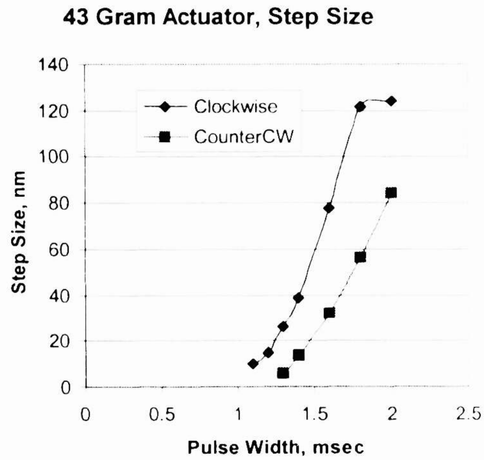

Figure 22. Measured motion of the prototype actuator. By adjusting the width of the pulse feeding the solenoid, the size of the step can be adjusted from a few nanometers to 0.1 μm.

The system that performs closed loop control of the mirror by driving the actuators based on wavefront data was build by ThermoTrex in San Diego. The initial implementation of this system uses Picomotor actuators from New Focus. These actuators and their drive electronics are available off the shelf and they have excellent performance at room temperature. These actuators will be replaced by the cryogenic models built at the U of A.

7. CONCLUSIONS

The 2-m NGST Mirror System Demonstrator is underway at the University of Arizona. We expect this to demonstrate diffraction limited performance at 35 K in a cryogenic test facility being built at Marshall Space Flight Center.

Due to a flawed substrate, we have not yet demonstrated system performance with the 2-m mirror. However, we have made the critical technology demonstrations that prove this method to work.[1] We manufactured a 53-cm prototype mirror and verified the performance using interferometry. We made a 1-m launch test to verify that the acoustic loading will not damage the mirror. We have demonstrated an actuator that achieves 5 nm resolution at cryogenic temperatures. We have also demonstrated wavefront sensing and mirror control technologies that can be implemented to provide the closed loop control.

ACKNOWLEDGMENTS

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