Ultralightweight active mirror technology at the University of Arizona

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ABSTRACT

Lightweight mirrors for space can be made using a thin flexible substrate for the optical surface and a rigid lightweight frame with actuators for support. The accuracy of the optical surface is actively maintained by adjusting the actuators using feedback from wavefront measurements. The University of Arizona is now is the final stages of fabricating two such mirrors. A 2-m NGST Mirror System Demonstrator, with an areal density of 13 kg/m^2, is being built for NASA and will be tested at cryogenic temperatures. A 50 cm development mirror, with an areal density of only 5 kg/m^2, is also being fabricated. This paper discusses the fabrication processes involved with both of these mirrors.

Keywords: space optics, lightweight mirrors, active optics

1. INTRODUCTION

Conventional mirrors use stiff glass blanks that can withstand polishing loads, launch, and the final operating environment. These mirrors are usually made from low expansion glass, formed into closed back shapes that achieve a good stiffness-to-weight ratio. The sections of the structured glass must be thick enough (>> 1 mm) to be safely handled, polished, and launched. The mirror itself must be deep enough (~10% of the diameter) to achieve good stiffness. This geometry limits the mass density for large mirrors in operation to greater than 30 kg/m^2, although there are developmental efforts to improve this. Figures 1 and 2 show two such mirrors, the 8.4-m, 16,000 kg primary mirror for the Large Binocular Telescope, and the 2.4-m, 830 kg primary mirror from the Hubble Space Telescope.

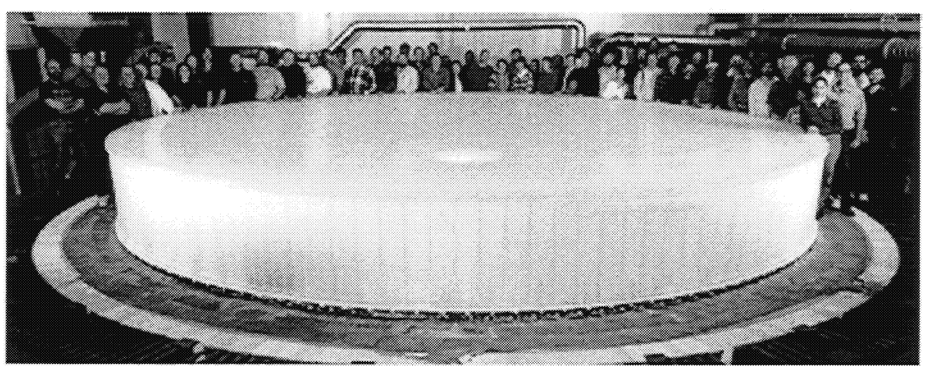

Figure 1. 8.4-m borosilicate glass mirror blank for the Large Binocular Telescope.

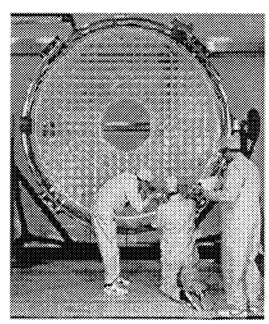

Figure 2. 2.4-m ULE glass blank for the Hubble Space Telescope.

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We present a mirror design that does not rely on the glass for stiffness or stability; this allows for very lightweight mirrors. The concept is shown in Figure 3, and it involves the following key points:

- Use a curved glass membrane with a reflective coating as the optical surface.
  We fabricate these membranes as a low-stress optic from a thicker glass substrate. For optimal performance, we use glass with a low CTE at the specified operating temperature.
- Support the membrane using active control via an array of actuators.
  We use remotely driven fine pitch screws for the actuators because they make small, reproducible steps; they are stiff and require no power to hold their position; and they work at cryogenic temperatures.
- Maintain system stiffness with a highly optimized composite backing structure.
  Stiff structures are made with incredibly thin components by bonding sheets of composite carbon fiber laminates together.
- Drive the actuators to maintain the shape of the mirror, based on input from a wavefront sensor.
  The active control, based on star light, compensates for substrate stability, fabrication errors, and deployment errors.

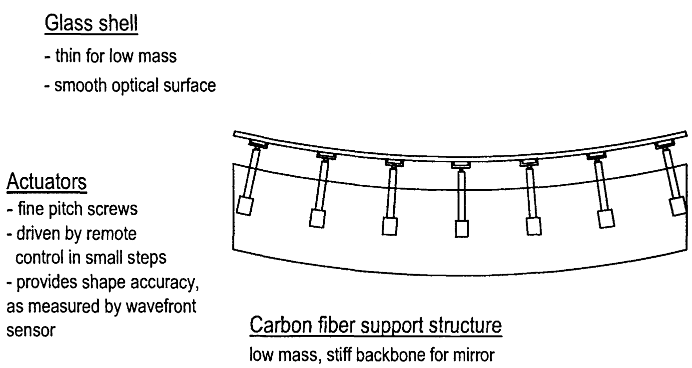

Figure 3. Active mirror concept showing glass membrane, actuators, and support structure.

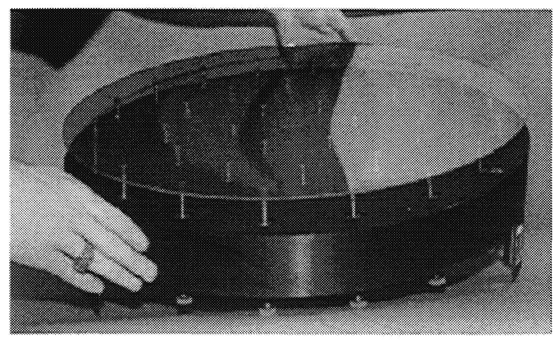

Figure 4. A prototype mirror, weighing about 20 kg/m^2. This mirror used a 2-mm Zerodur membrane on 36 actuators and a composite support structure.

The actively controlled mirror has several important advantages over a fixed mirror. It eases requirements for thermal stability of the structure, which can be driven by large temperature changes or by thermal gradients. It also accommodates changes in shape due to material instability over the life of the mirror. Also, the membrane does not have to be initially polished accurately on large scales because it can be deformed into shape. Basically, anything that negatively affects the mirror surface can be corrected. In fact, mirrors of this type are used with fast actuators and control electronics to remove the phase effects from the atmosphere in *real time.*[1]

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; 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.[2]

2. FABRICATION OF 2-M NMSD

A 2-m NGST Mirror System Demonstrator (NMSD), is being fabricated at the University of Arizona. The 2-mm glass shell is made from borosilicate glass, which has zero CTE at the 35 K operating temperature. The support structure is made by Composite Optics, Inc. The actuators are manufactured at the University of Arizona. This mirror is expected to achieve < 30 nm rms performance at 35 K, and the total mass of the 2 meter mirror, including glass, composite support, actuators, and cabling, is only 40 kg.

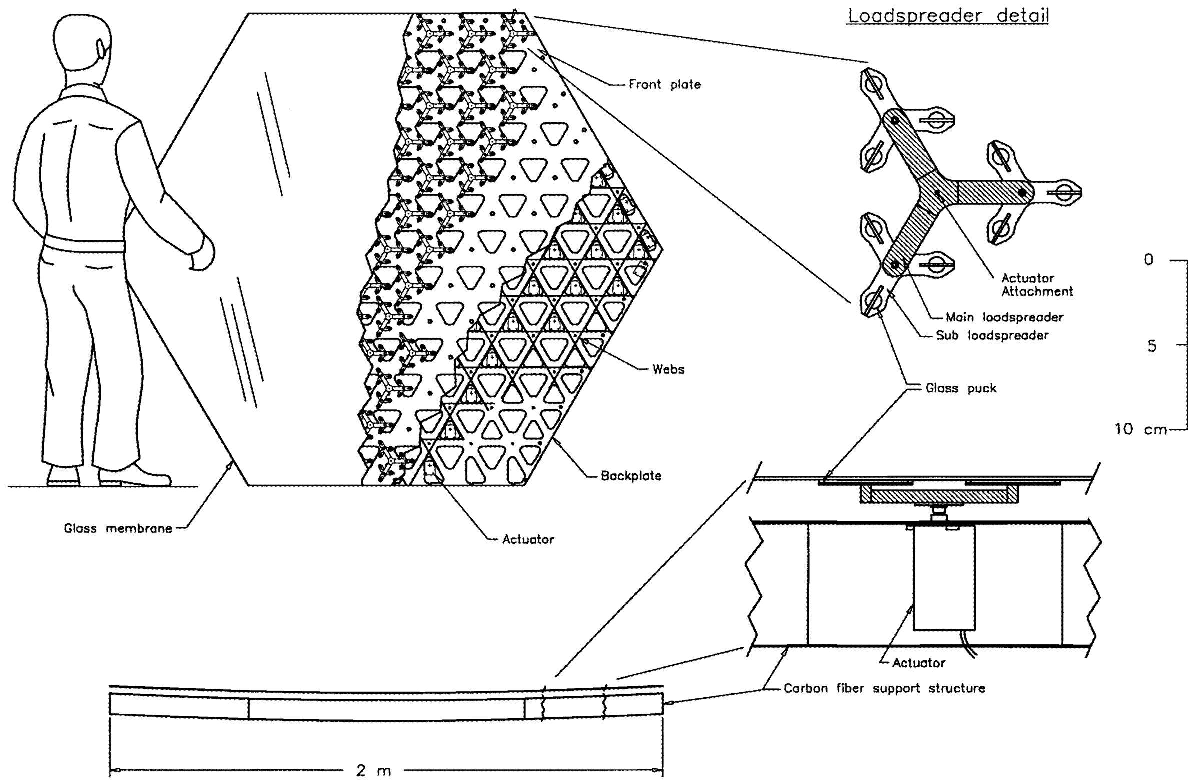

Figure 5. 2-meter NGST Mirror System Demonstrator.

We fabricated two glass shells for this mirror. The manufacture of the first shell, described previously,[3] suffered flaws in the initial casting that caused it to fail in subsequent operations. The basic manufacturing steps for the second substrate are shown below in Fig. 6. We cast a 50 mm thick blank from Ohara's E6 borosilicate glass using the 8-m rotating furnace at the Steward Mirror Lab. This casting achieves high homogeneity because it starts from a complete block of select glass that was made in a single pot. It was then melted and shaped into a 2.2-m blank.

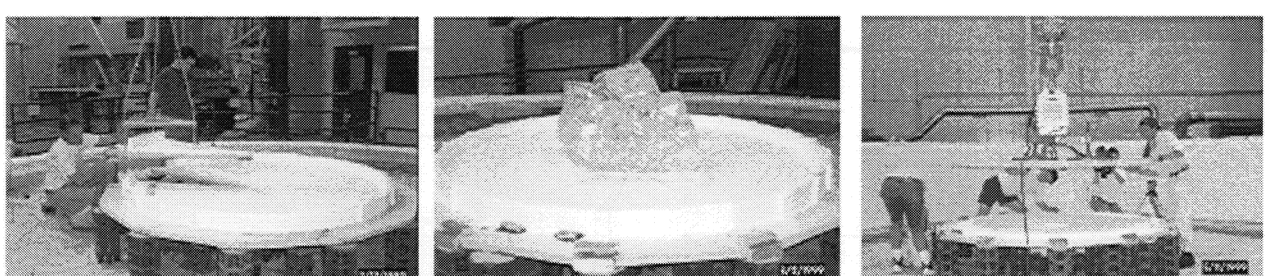

Figure 6. Manufacture of the E6 blank for the NMSD shell, including mold construction, preparation to flow out glass, and final substrate.

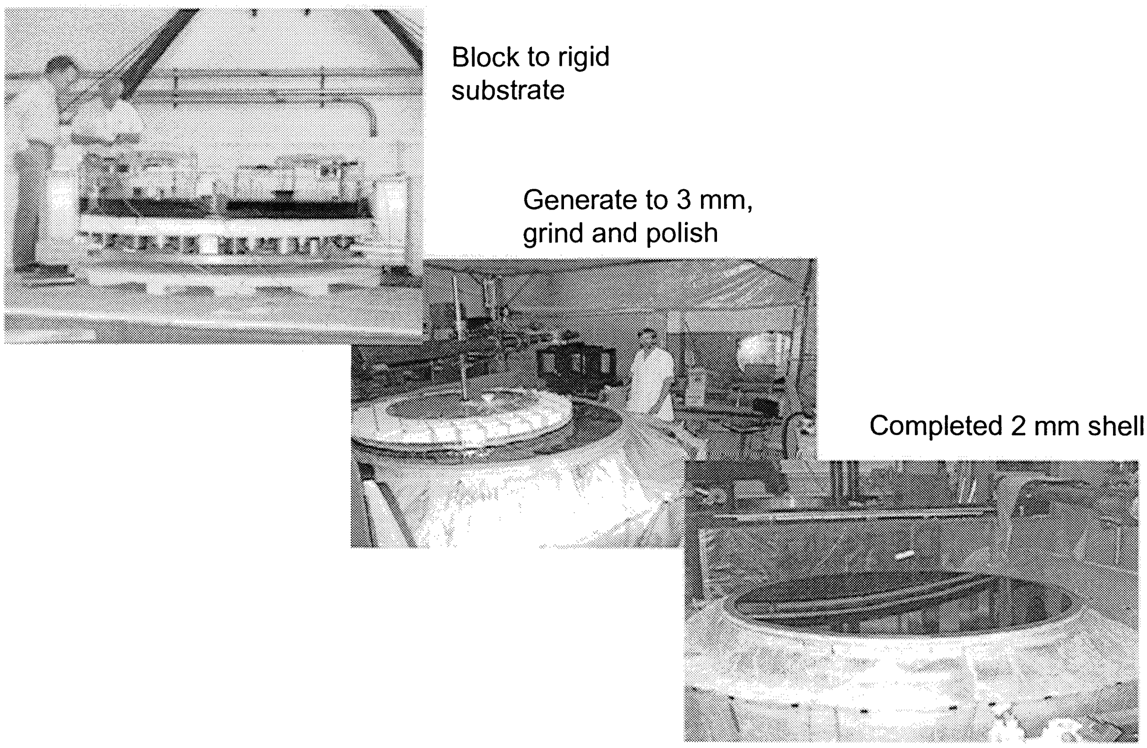

Figure 7. Completion of the 2-m diameter glass shell for the NGST Mirror System Demonstrator.

The convex side of the 2.2-m blank was then generated and polished spherical. This will become the back of the completed membrane. Then this blank, about 35 mm thick, was blocked to a rigid substrate using pitch. The blank was held in an oven by a distributed support, while the liquid pitch layer was slowly squeezed out to its final thickness of 0.75 mm. After a slow cooling, the blank was rigidly bonded to the thick blocking body. Most of the glass was generated off, leaving a 3 mm thick shell still bonded to the blocking body. This was then ground to a 2 mm final thickness and polished using conventional methods. The 2.2-m circular membrane was then cut using a diamond saw into a hexagonal shape, 2 meters corner to corner. These operations are shown in Figure 7.

The finished membrane was separated from the blocking body by placing the assembly in a bath of hot oil and using buoyant forces to provide the separation forces, as shown in Fig. 8. Eighteen cylindrical floats were attached to the glass surface using RTV adhesive. The entire assembly was then placed in a 10-foot insulated tank which was filled with oil and heated to 250° F. Trim weights were placed on the floats to maintain a net upward buoyant force of 6.75 lbs at 250° F. The weights were trimmed as the membrane started to lift. It took about 12 hours to heat up, 6 hours to float off, and 12 hours to cool back down.

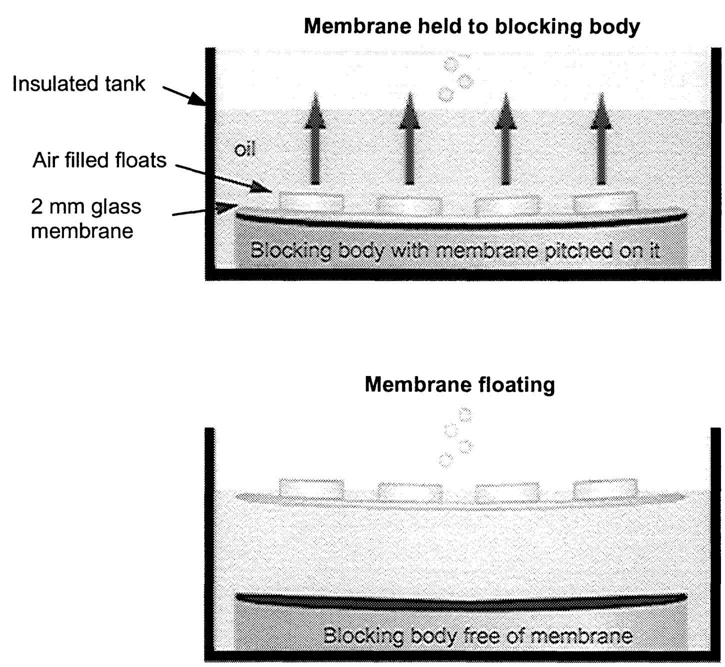

Figure 8. The completed membrane was separated from the blocking body in a bath of hot oil using buoyant forces.

After cooling, the glass was lifted out of the oil using an 18-point whiffle tree, Figures 10 and 11. The glass was cleaned with spray degreaser and placed on a transfer mechanism that matched the 18 lift points, Figure 12. The floats were then removed from the concave surface, and the glass was carefully cleaned.

At this point, the membrane rested on 18 points with the concave optical side face up. For the next operation, we attached the support hardware onto the rear, convex side. We used a full-size vacuum tool to handle the membrane as we flipped it over. The tool has a rubber interface with a convex surface that was replicated from the original concave surface of the membrane. Channels were cut in the rubber surface, and hoses were inserted to distribute the vacuum. To lift the membrane, this tool was lowered onto the membrane and attached by vacuum. Then the tool was lifted, removing the glass from the 18 point support, and set onto a cart that had trunnions for flipping and wheels for transfer. The cart and membrane assembly was moved to a clean room where the attachment hardware was bonded to the back of the membrane. The vacuum fixture supported the membrane during the bonding process.

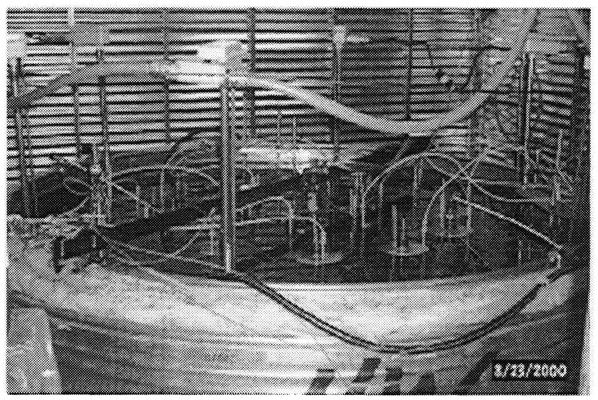

Figure 9. The blocking body with attached membrane is submerged in a heated oil bath. The floats, which are attached to the membrane are visible near the surface.

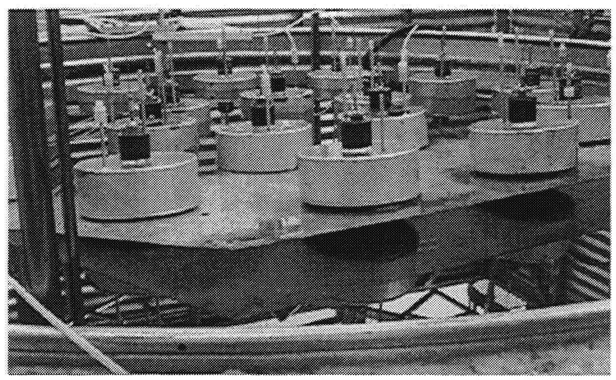

Figure 10. After floating free, the membrane is lifted from the oil using a whiffle tree attachment to the floats. It is tilted to allow the oil to flow out.

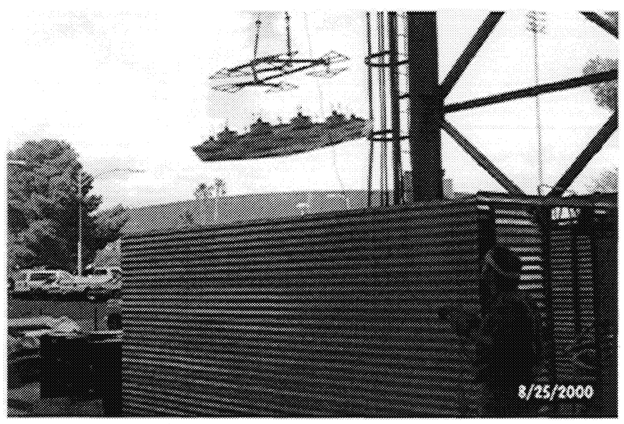

Figure 11. The deblocked membrane was lifted from the oil bath with an overhead crane.

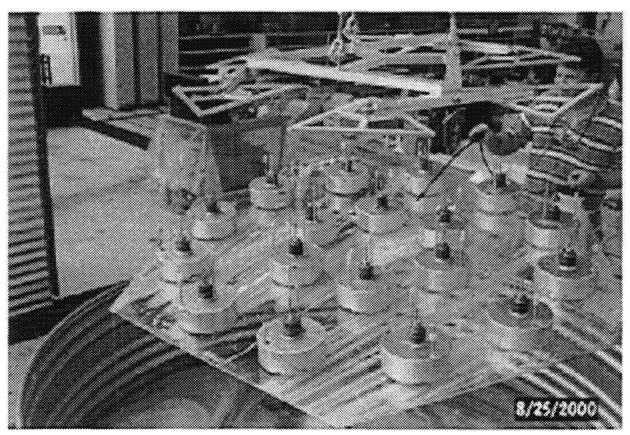

Figure 12. The oil was washed off the glass.

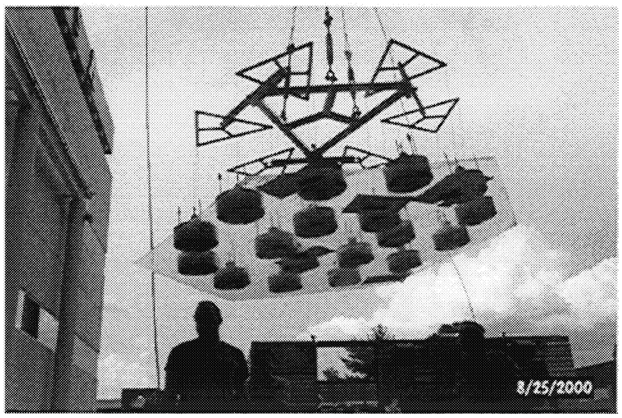

Figure 13. The completed membrane, hanging from its whiffle tree.

Figure 14. The membrane was set down onto another whiffle tree.

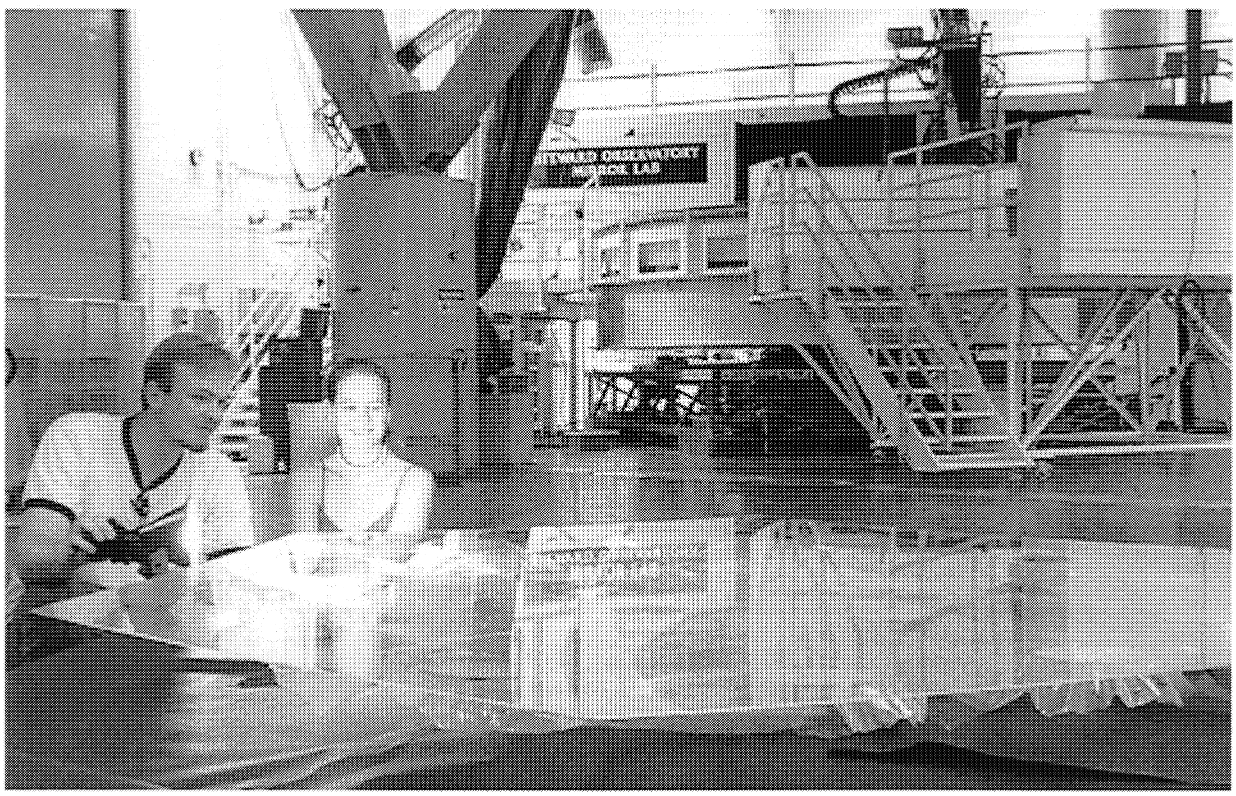

Figure 15. Completed 2 mm thick, 2-m hexagonal membrane for the NMSD mirror

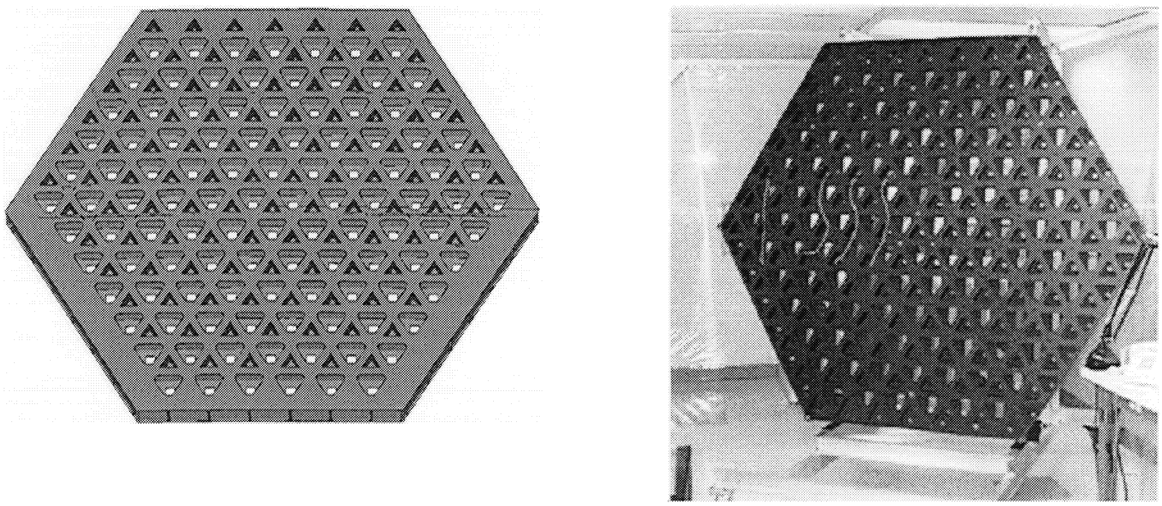

Figure 16. 2-m composite support structure for NMSD

The NMSD reaction structure is a low thermal strain, lightweight, graphite reinforced composite assembly, fabricated by Composite Optics, Inc. (COI) in San Diego. Obtaining adequate stiffness and strength from this assembly using COI's technology has proven to be straightforward. There is considerable latitude in selecting the thermal strain characteristics of the reaction structure. We select a low CTE at the intended operating temperature. The actuators can accommodate any distortion of the cell so the only effect of concern is the cell distortion between the facesheet correction cycles.

The actuators and control electronics for NMSD are now being manufactured at the University of Arizona. The actuators have demonstrated repeatable performance at ambient and cryogenic temperatures. The actuator and some data at 35K are shown below. The electronics are being built at the University of Arizona to enable robust operation of the actuators at both ambient and cryogenic temperatures.

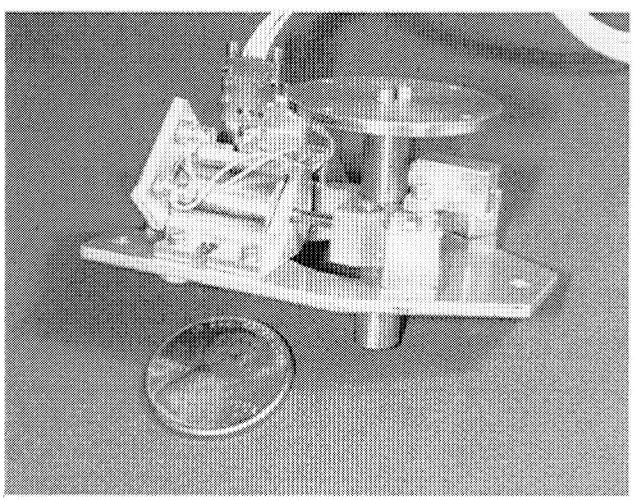

Figure 17. University of Arizona NMSD actuator

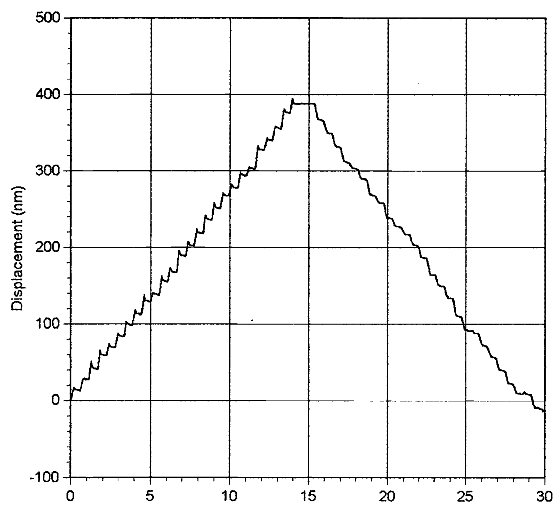

Figure 18. Measured actuator performance at 35K.

The system assembly for NMSD is now underway and we expect to perform ambient temperature optical testing at the University of Arizona in early 2001, followed by cryogenic testing at NASA Marshall Space Flight Center a few months later.

3. 0.5-M ULTRALIGHTWEIGHT MIRROR DEMONSTRATION

In addition to the 2-m NMSD mirror, we are also nearing completion of a 0.5-m mirror with density of only 5 kg/m^2. This is funded by the National Reconnaissance Office (NRO) *Director's Innovative Initiative*. In this design, we have pushed the technology as far as we can (given the time and cost constraints) to make the mirror lighter. We have a 1 mm thick glass membrane and tiny custom actuators. The design philosophy is the same as for the NMSD.

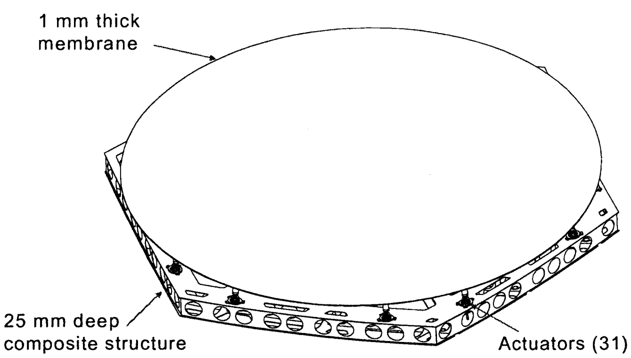

Figure 19. Front view of the 0.5-m mirror.

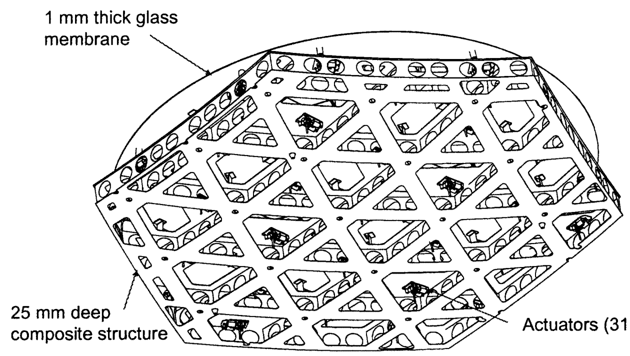

Figure 20. Back view of the 0.5-m mirror.

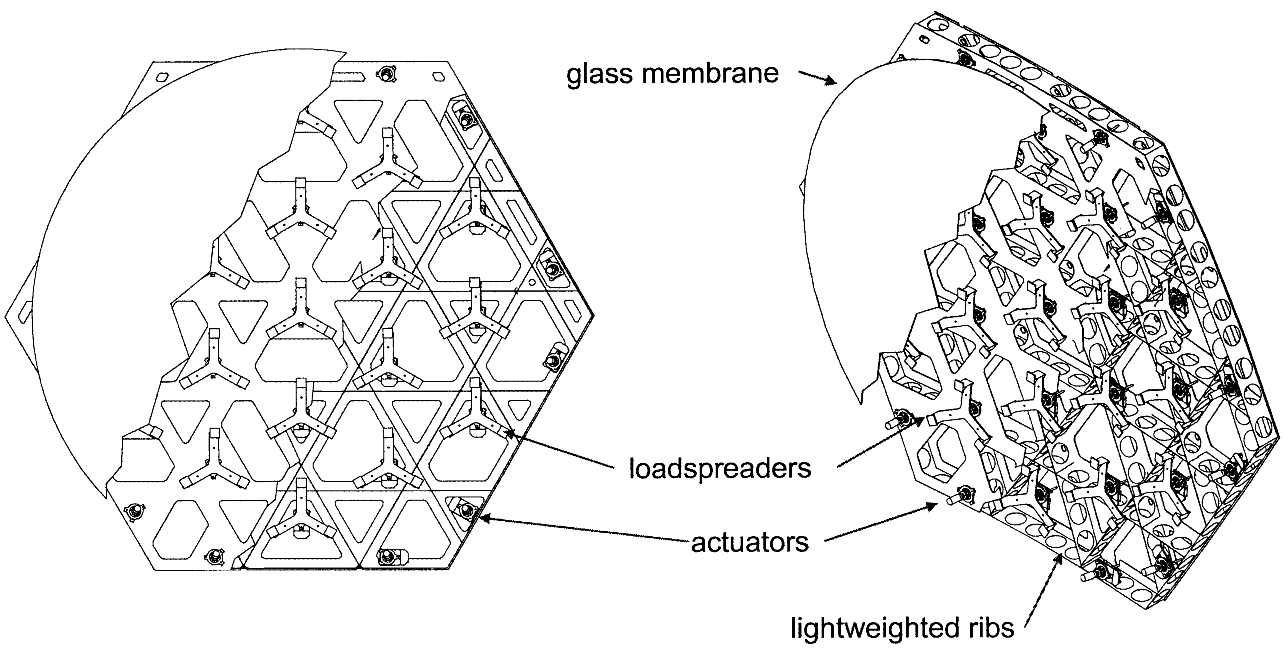

Figure 21. Front view of the 0.5-m mirror.

The glass was manufactured at the University of Arizona and is slightly different than the 2-m NMSD. For the 0.5-m mirror, we finished the concave optical surface first while the substrate was thick. Then we blocked it down with pitch and generated, ground, and polished the convex side. This order is preferable because strain from blocking only gets into the back surface, not the optical surface. Because this mirror is smaller, we did not need to deblock the glass in hot oil. We heated the assembly in an oven and slid the membrane off the blocking body. The membrane was then cleaned and coated with aluminum.

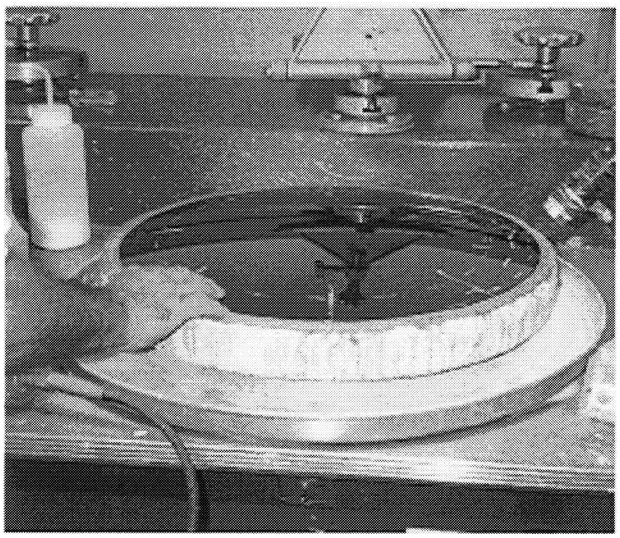

Figure 22. Polished membrane with concave side blocked down.

Figure 23. Deblocking the finished 1 mm thick glass membrane. The ring fixture was used for handling the mirror during deblocking and coating.

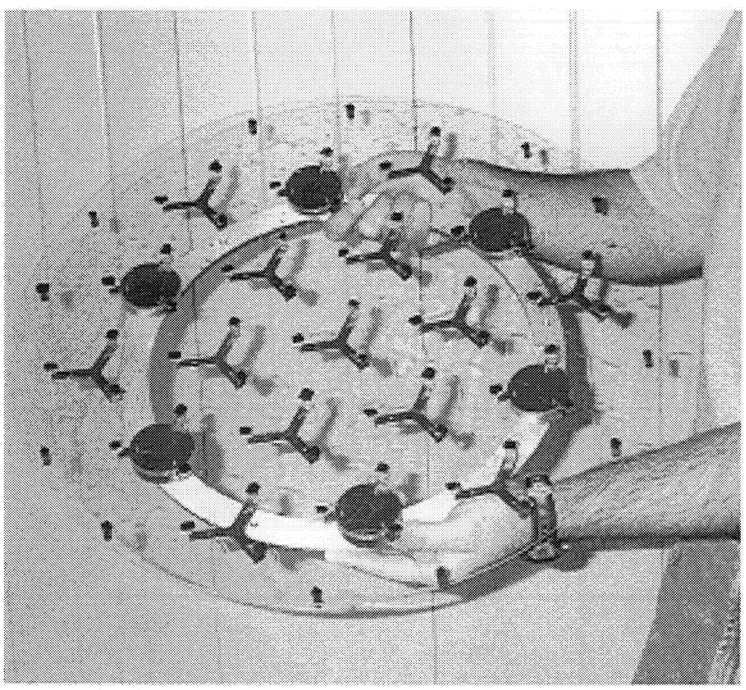

Figure 24. Finished 1 mm thick glass membrane after deblocking and cleaning.

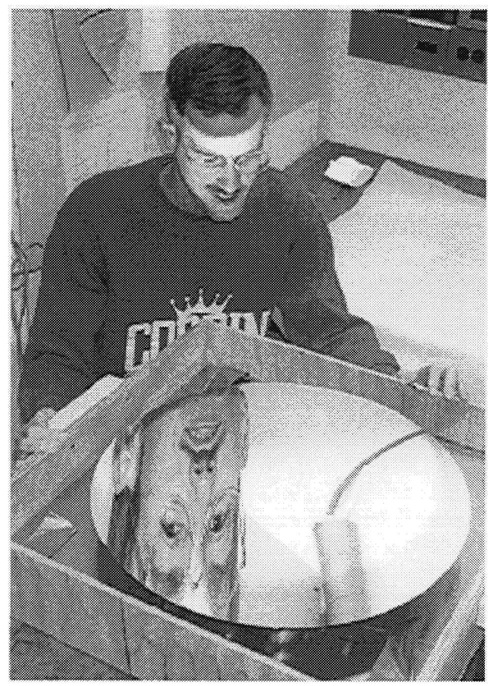

Figure 25. Glass membrane after coating with aluminum.

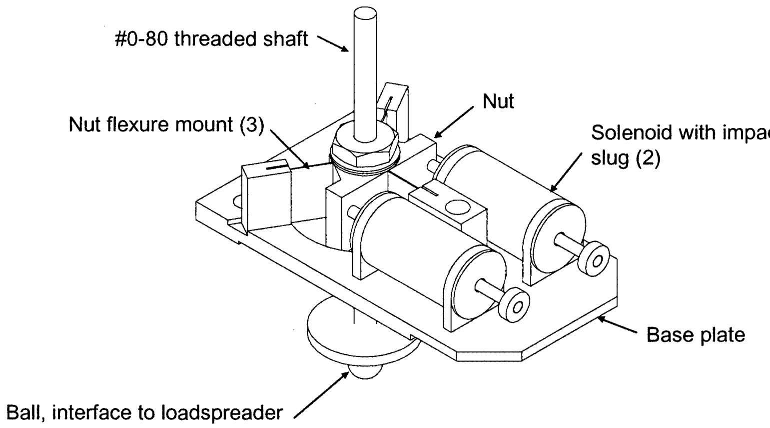

Figure 26. Tiny actuators for the 0.5-m mirror. These actuators weigh 5 grams apiece and make 20 nm steps without hysteresis.

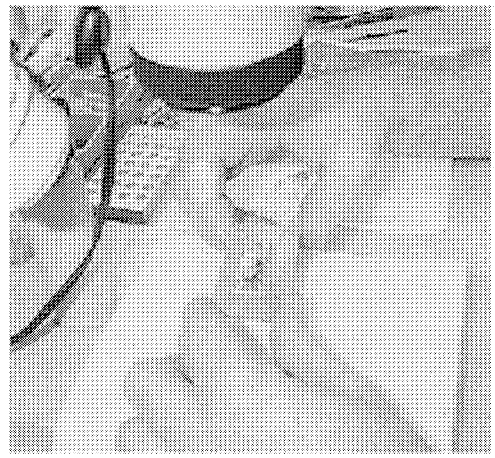

Figure 27. The tiny actuators must be assembled under a microscope.

The actuators are similar in design to the NMSD actuators, but they are much smaller. Each actuator has a mass of 5 grams, plus 2 grams per actuator for cabling and connectors. These units have been demonstrated to achieve 20 nm step size. The control electronics for these actuators is identical to those for NMSD. The actuators are driven by pulses that are made by analog electronics under computer control. The software that controls the mirror allows individual actuators to be controlled, and it also interfaces with an interferometer.

The glass attachment is different for the 0.5-m mirror. Most of the actuators apply their force through 3-point load spreaders. This limits the local effect of the actuator, and it also spreads out forces to reduce stress in the hardware. The thin glass is quite susceptible to distortions from these attachments. We have engineered hardware and assembly processes to that do not cause extraneous stresses, Figure 29.

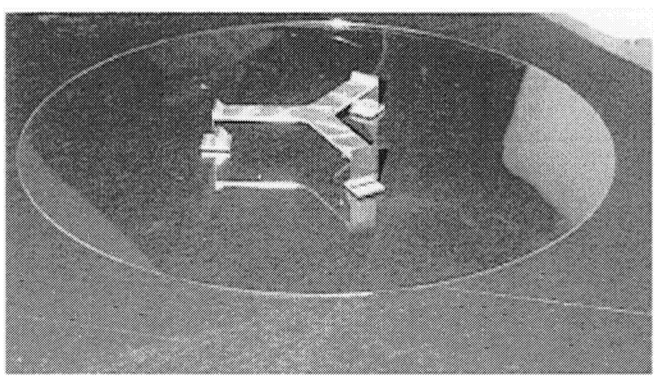

Figure 28. A mockup of a loadspreader on a sample glass, 0.7 mm thick. The assemblies are bonded in place using Q3-6093 silicone adhesive.

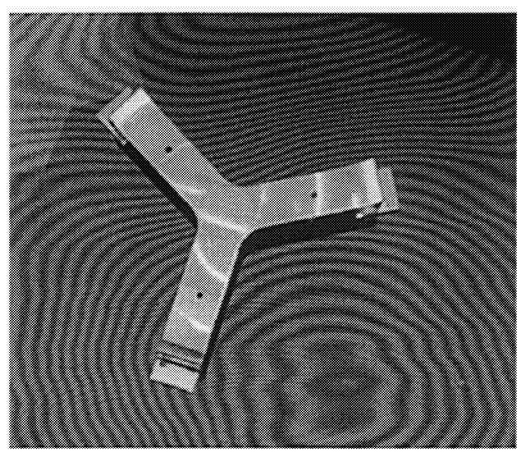

Figure 29. Interferometric measurement shows that there are no local stresses in the 0.7 mm sample glass from the attachment. The large scale distortions are in the substrate.

The support structure for this mirror was designed at the University of Arizona and fabricated by Composite Optics, Inc. To achieve the required level of light weighting, thin laminates were used and numerous cutouts were made in the facesheet, backsheet, and ribs. The facesheet and backsheet are 0.5 mm thick, and the ribs are 0.25 mm thick.

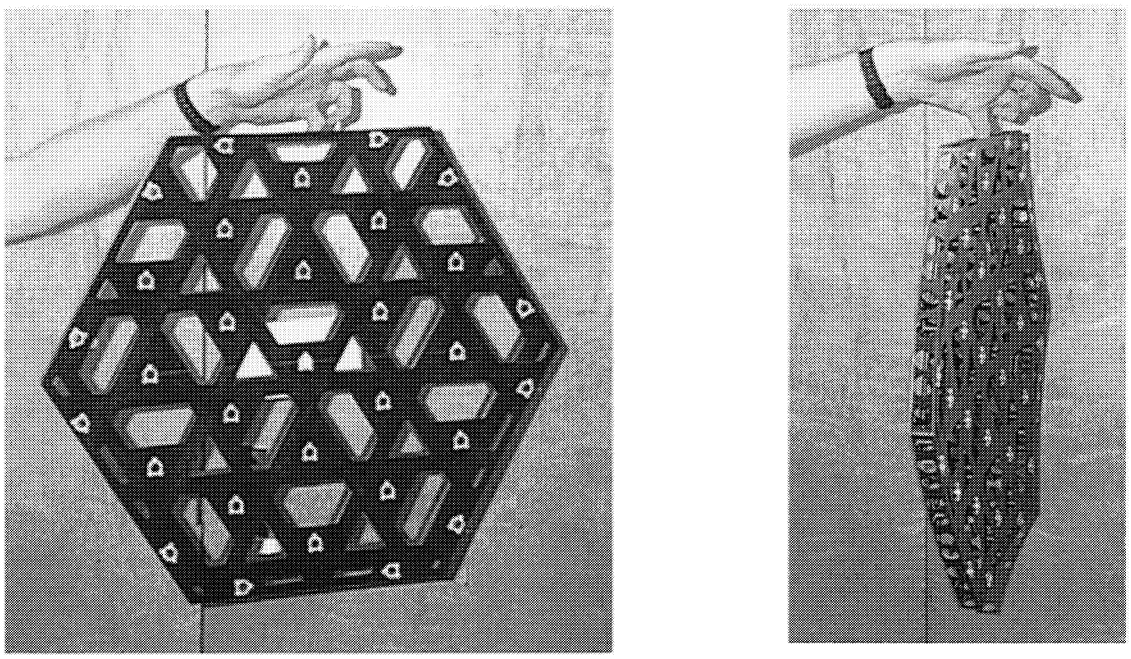

Figure 30. Front and side views of the 300 gram composite support structure.

The 0.5-m mirror is now in final assembly and is expected to be operational in January 2001. This mirror will be tested at ambient temperature at the University of Arizona.

4. PERFORMANCE OF LIGHTWEIGHT ACTIVE MIRRORS

The two mirrors described above are capable of excellent optical performance. The principal limitations in these mirrors come from stress in the membrane that must be removed using the actuators. The actuator forces will then cause residual figure errors. We also have difficulty assessing the mirror quality because of inevitable self-weight deflection. We use a combination of hardware and software to remove these effects.

The 2-m NMSD is expected to have errors of only 27 nm rms at the cryogenic temperature of 35 K. To measure this, we will install hardware that removes most of the gravitational effects. We expect to see 60 nm rms surface distortions from the mounting, which we will subtract from the data analytically. In space, of course, the gravitational effects are not present. The 0.5-m mirror is expected to have an rms surface error of 32 nm. This mirror will be measured with the optical axis vertical, and we will need to measure and remove 310 nm rms surface distortions from self-weight deflection.

The mass summaries for the two mirrors are given below in Table 1.

Table 1. Mass summaries for the NMSD and NRO mirrors

	NMSD under construction (kg/m^2)	NRO ultra lightweight design (kg/m^2)
Glass membrane	4.4	2.5
Actuators, electronics, and cabling	2.5	0.9
Load spreaders and glass attachments	2.0	0.4
Launch restraint hardware	0.3	0.1
Carbon fiber support structure	3.2	1.1
Total mass per square meter	**12.4**	**5.0**
Total mass for an 8-m mirror	**623 kg**	**250 kg**

5. CONCLUSION

We show an interesting technology for lightweight mirrors using glass membranes and an active control system. These mirrors achieve very high performance with very low mass. This technology serves as a useful starting point for two other applications. This design can be further lightweighted for longer wavelength applications. A thinner membrane, made from a less dense material, can be used, and the number of actuators can be reduced. Giant space telescopes can be designed to use near-flat membrane optics.[4,5] Mirrors of this sort can achieve mass densities of << 1 kg/m^2, including the support and controls. They do not need an array of actuators to maintain their shape, but they use an actively controlled perimeter, possibly with electrostatic pressure to induce small amounts of curvature.[6] These telescopes use the near-flat mirrors as collectors, with the active mirrors described here for the other elements.

ACKNOWLEDGMENTS

This paper summarizes work being performed by a talented and dedicated team of scientists, engineers, technicians, and support staff. None of this would be possible without their talents and efforts.

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