THE CASTING OF THE 6.5m BOROSILICATE MIRROR FOR THE MMT CONVERSION

J. M. Hill and J. R. P. Angel
Steward Observatory, University of Arizona
Tucson, AZ 85721

Abstract

We describe the process of casting a 6.5 meter diameter borosilicate honeycomb mirror. Descriptions and photographs cover the beginning of mold building in June 1991 through the casting process in April 1992 and finally a look at the finished blank in June 1992. This mirror will be used in the MMT Conversion project which will upgrade the existing Multiple Mirror Telescope to a monolithic 6.5 meter aperture. This casting also represents the culmination of a decade long development project to produce affordable 8 meter mirrors which deliver excellent images.

Introduction

As part of the continuing effort to produce high performance and affordable mirrors for large telescopes, the Steward Observatory Mirror Laboratory has cast a 6.5 meter diameter borosilicate honeycomb mirror blank. The casting of this large mirror represents the final step in developing the technology and techniques necessary to produce 8 meter lightweight mirror blanks. The new 6.5 meter F/1.25 parabola will be installed in the Multiple Mirror Telescope operated by the University of Arizona and the Smithsonian Institution.

The honeycomb structure provides these large mirrors with improved mechanical performance and improved thermal performance compared to more conventional solid blanks. The honeycomb structure provides an order of magnitude increase in mechanical stiffness compared to the same mass of glass in a solid meniscus. This stiffness allows the large mirror to better resist wind forces and allows us to build lighter telescope structures. By ventilating the honeycomb with ambient temperature air, the thermal time constant of the mirror can be reduced to less than one hour. This short thermal time constant allows the honeycomb to track the mountaintop air temperature and reduce the effects of mirror seeing.

A series of smaller mirrors for telescopes have been produced as part of the technology development effort. This series included the successful casting of three 3.5 meter diameter borosilicate honeycomb blanks in 1988 and 1989. These have been described by Goble *et al.* (1989).

The Furnace

Since 1990, the furnace on the rotating turntable has been expanded to allow for the casting of mirrors up to 8.4 meters in diameter. The upgrades to the furnace control system have been described by Hill *et al.* (1990). Figure 1 shows a cross-section of the furnace with the 6.5 meter honeycomb mold inside. Figure 2 shows the upper section of the furnace being lowered into place. The entire inside surface of the shell and the hearth are lined with 8 kilowatt electric heaters. The temperature of the glass and mold is controlled with 1 $°C$ by servoing these 269 heaters to obtain a uniform surface temperature. The furnace control system contains 630 type N thermocouples which are used for temperature control and monitoring.

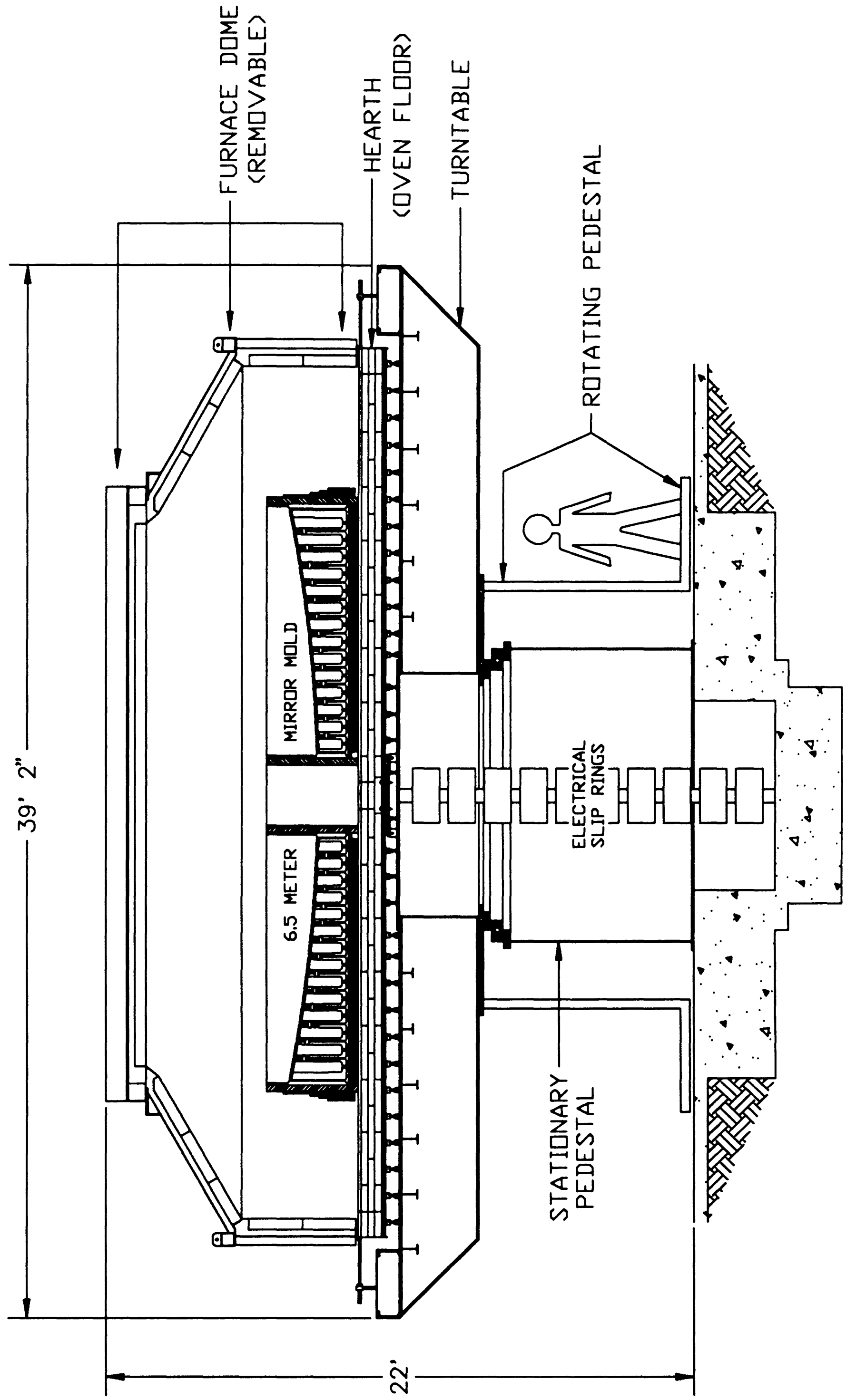

Figure 1: This figure shows a cross section of the rotating furnace with the 6.5 meter honeycomb mold inside.

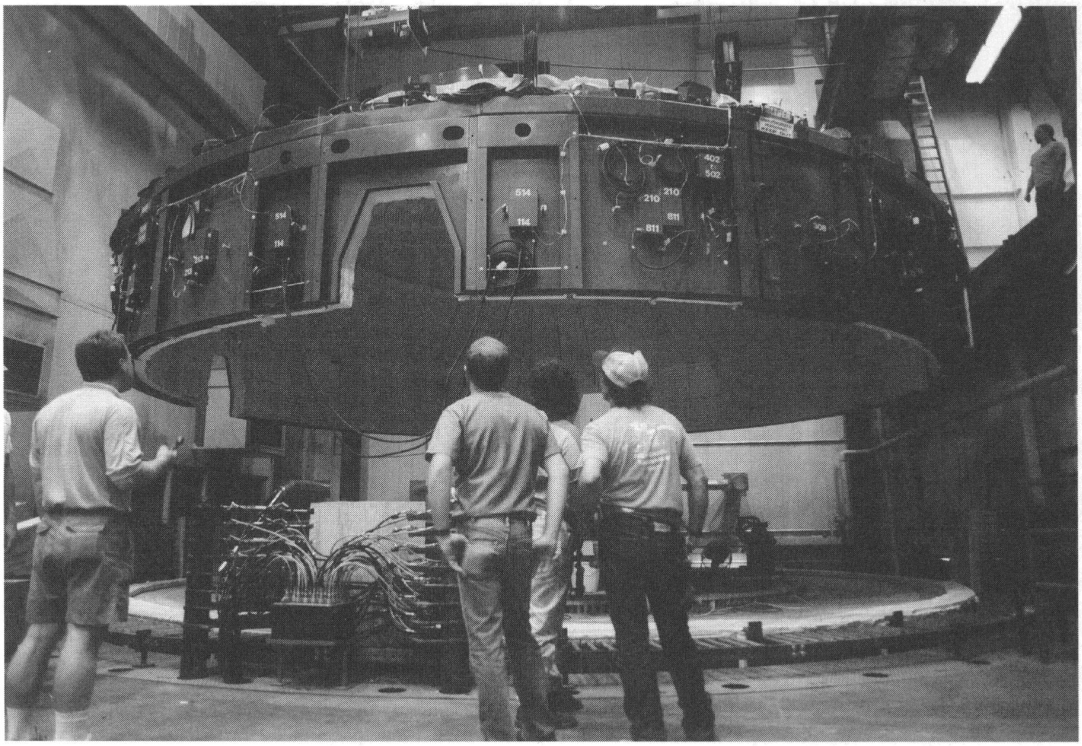

Figure 2: This photo shows the upper shell of the furnace being lowered into place during the early phases of mold assembly. This section of the furnace is removed by crane to allow access for mold assembly and to remove the completed mirror blank. UA photo by Lori Stiles

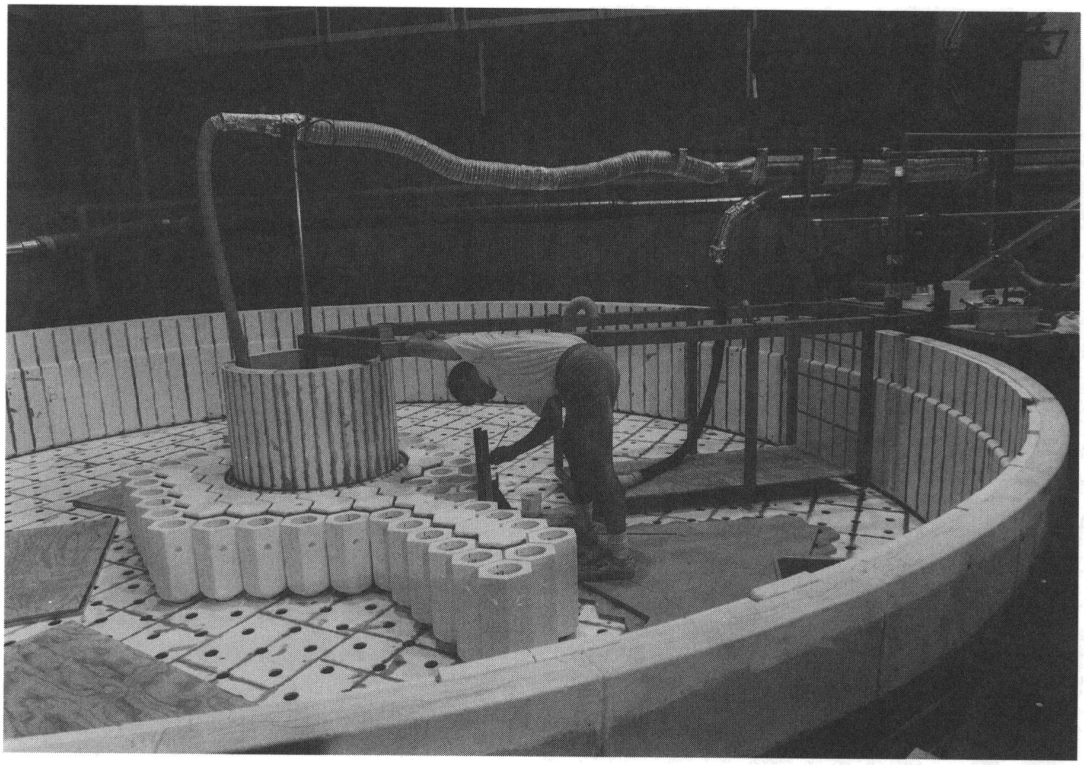

Figure 3: This photo shows R. Lutz installing one of many hexagonal core boxes in the 6.5 meter mold. Each of these boxes will form a void in the finished honeycomb. Silicon carbide bolts hold the box against buoyancy forces. The boxes or cores are also pinned to each other to keep them aligned vertically. A special fixture aligns each box with respect to holes in the grid of hexagonal tiles on the floor of the mold. After the bolt has been tightened and the cross-link pins installed, a ceramic fiber cap is glued on each core box. The cantilevered bridge provides human and utility access to the mold. Some of the Inconel steel containment bands may be seen in the right foreground. UA photo by Lori Stiles

Mold Construction

In June 1991, the assembly of the complex honeycomb mold began inside the furnace. The borosilicate honeycomb is formed by melting chunks of glass into a complex ceramic fiber mold. This mold is removed from the honeycomb after the blank has been annealed. Figure 3 shows the ceramic fiber hexagonal boxes being bolted to the floor of the mold. The boxes are vacuum formed out of aluminasilica fiber into the rough hexagonal shape by the Rex Roto Corporation. These boxes are then fired to 1180 $°C$ before being machined to their final shape on a NC milling machine. The hexagonal core boxes are held down against their own buoyancy in the molten glass by silicon carbide bolts. These custom bolts have been injection molded by the Ferro Corporation. The bolts are installed before the tops of the core boxes are glued in place with ceramic adhesive. The bolts attach to hexagonal tiles that make up the bottom of the mold. These tiles are arrayed on the flat furnace hearth and may be seen in Figure 2. Figure 4 shows the final assembly of the 6.5 meter mold in January 1992. After the mold is assembled and inspected, it is heated (empty) to 1180 $°C$ to drive off volatiles and cure the ceramic adhesive bonds. This prefire step also serves to test the furnace control system. Figure 5 shows the geometry of the honeycomb structure and the 1020 hexagonal cores.

The 6.5 meter mold is surrounded by a segmented wall built of castable SiC cement. These sections of a cylinder are held together against the hydrostatic pressure of the molten glass by 80 Inconel steel bands. These bands wrap 90 degrees around the mold cylinder or tub and then exit the furnace. Outside the furnace, pneumatic cylinders pull on the bands to contain the liquid glass while allowing the mold to expand and contract. As the mirror cools, the pressure in the cylinders is reduced to avoid crushing the fragile honeycomb structure. Each band has a 25 x 50 mm cross-section and exerts 2000 N of tension while the furnace is at 1180 $^{\circ}C$. Thermal expansion causes each of these bands to grow by more than 100 mm as the furnace is heated.

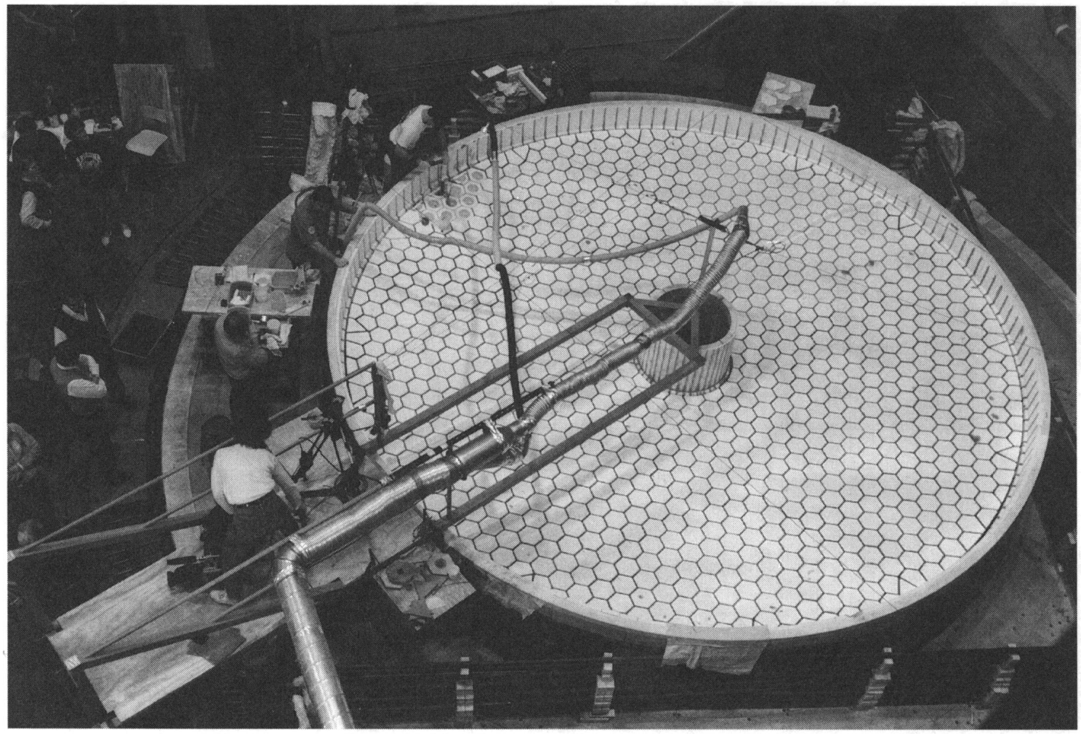

Figure 4: This photo shows an overhead view as the last few cores are installed in the 6.5 meter honeycomb mold on January 23, 1992. 1020 ceramic fiber boxes make up the voids in the honeycomb blank. About 6 weeks were required to install all of the cores. Vacuum hoses are used to collect any stray ceramic dust. The pneumatic cylinders which pull on the Inconel bands can be seen in the upper corners of the photo. After being fired while empty, the mold was filled with 10 tons of glass chunks. UA photo by Lori Stiles

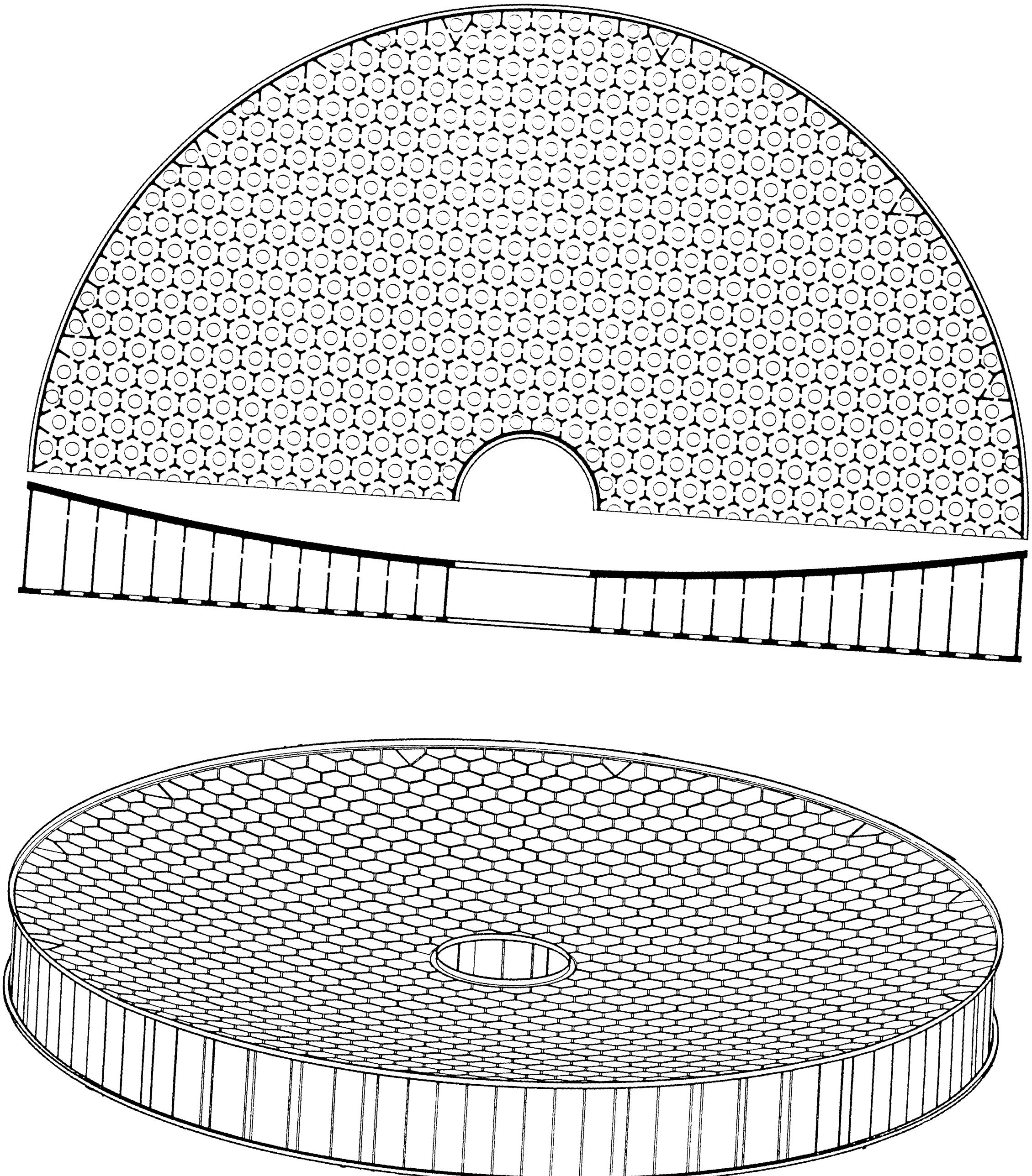

Figure 5: This figure shows the honeycomb geometry used for the construction of the 6.5 meter mold. The honeycomb blank is 6.5 meters in diameter. The hexagonal cores are spaced on 192 mm centers with 12 mm wide gaps between them to form the ribs of the honeycomb. The front and back faceplates of the mirror were cast at 42 and 30 mm thickness respectively. These will be ground down to 28 and 25 mm during the optical finishing process. The finished honeycomb will be slightly over 20% of solid density.

Glass Loading

Chunks of E6 low expansion borosilicate glass are produced by the Ohara Corporation in Japan. The 5 kg chunks with broken surfaces melt together smoothly to form the continuous honeycomb. The expansion coefficient of this glass is $2.9 * 10^{-6}$ per $°C$ and Ohara has produced over 25 tons with an expansion coefficient uniformity of $2 * 10^{-8}$ per $°C$. The relatively low softening temperature of the borosilicate glass allows us to form it into the complex geometry of the honeycomb blank in a single casting operation. Figure 6 shows the chunks of glass being hand-loaded into the honeycomb mold in March 1992.

Figure 6: This photo shows Mirror Lab technicians Warner, Lutz and Watson loading chunks of E6 borosilicate glass into the honeycomb mold. The glass must be carefully loaded by hand to avoid damaging the friable honeycomb mold. 9550 kg of glass was loaded into the mold. UA photo by Lori Stiles

Casting and Annealing

On March 29, 1992, we began the heating process for the casting of the 6.5 meter honeycomb. The mold was heated slowly to 500 $°C$ and held there for 12 hours to allow a final test of the temperature control system. At that point, heating continued at a rate of 20 degrees per hour. As the glass began to soften at 700 $°C$, the rotation speed of the furnace was ramped to 7.40 rpm (April 2, 1992). The rotation causes the glass to form a parabolic surface 3 cm above the tops of the core boxes. Rotating the furnace during casting saves the cost of adding and then grinding off an additional 10 tons of glass. Figure 7 shows the rotating furnace. The mirror was allowed to cool after spending several hours at the peak temperature of 1180 $°C$. Figure 8 shows the 3 month long annealing and cooling cycle. Some photos of the melting chunks of glass appear in the July 1992 issue of Sky & Telescope magazine.

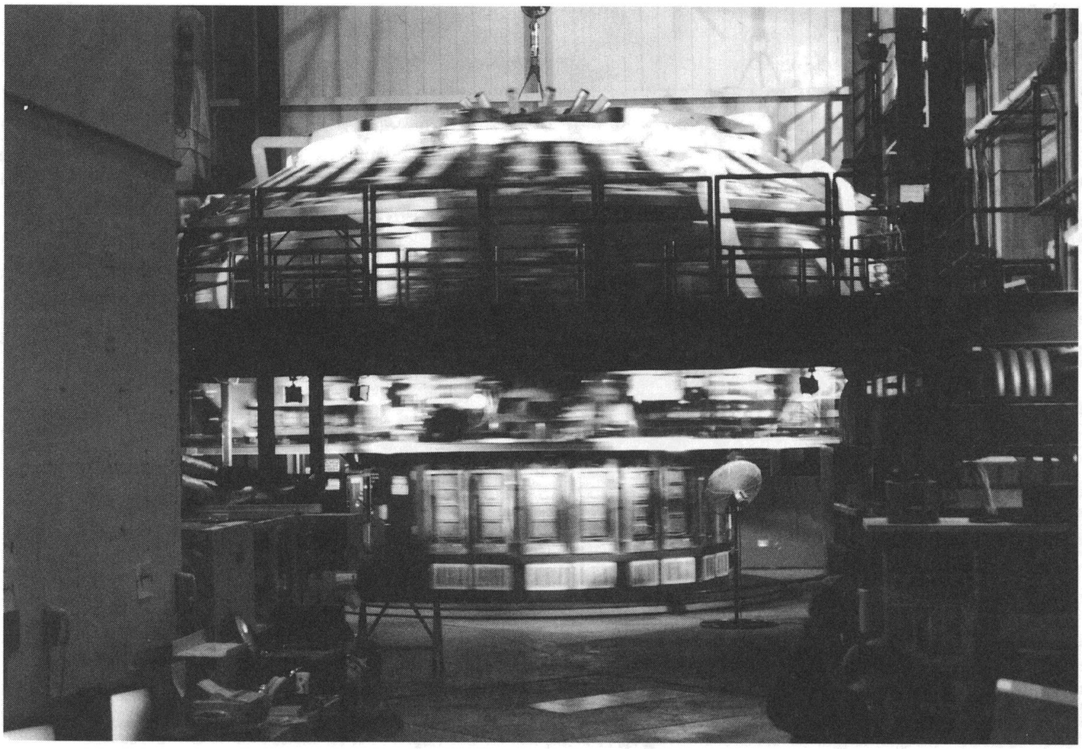

Figure 7: This photo shows the rotating furnace during the casting of the 6.5 meter mirror. The upper section is the actual furnace and the lower section below the turntable holds the corotating electronics and computers which control the temperatures of the heating elements. The ducts at the center of the top intake air to keep the wiring cool. The furnace was rotated at 7.40 rpm for 70 hours by two 40 horsepower DC servomotors. The average speed was controlled to 0.1%. One of these motors was operated from normal AC line power, while the other was operated from diesel generator backup power to assure that spinning would continue in the event of a power failure. UA photo by Lori Stiles

Results

After three months of patient waiting and watching, the mirror finally reached ambient temperature in late June. Initial inspection has shown that there are several dozen $\sim$1 cm bubbles on the surface. The average faceplate thickness is 35 mm, thinner than the target but still well over the 28 mm required for the finished blank. As of this writing, no significant defects have been identified. In Mirror Lab parlance, "It's a keeper."

The mirror will be lifted from the furnace in August 1992 after it has been inspected and the surrounding bands and tub walls have been removed. It will be turned to a horizon-pointing orientation where the soft refractory cores will be removed with a high-pressure water spray nozzle. After a final inspection the mirror will be transferred to the polishing section of the Mirror Lab. Diamond generation of the asphere is expected to begin in early 1993. The mirror will then be polished to a precise parabolic shape with the stressed lap. Martin *et al.* (1992) describe recent work with the stressed lap on 3.5 meter mirrors.

Conclusions

The first attempt at casting a 6.5 meter diameter borosilicate honeycomb mirror at the Steward Observatory Mirror Lab has been successful. This success will pave the way for additional castings between

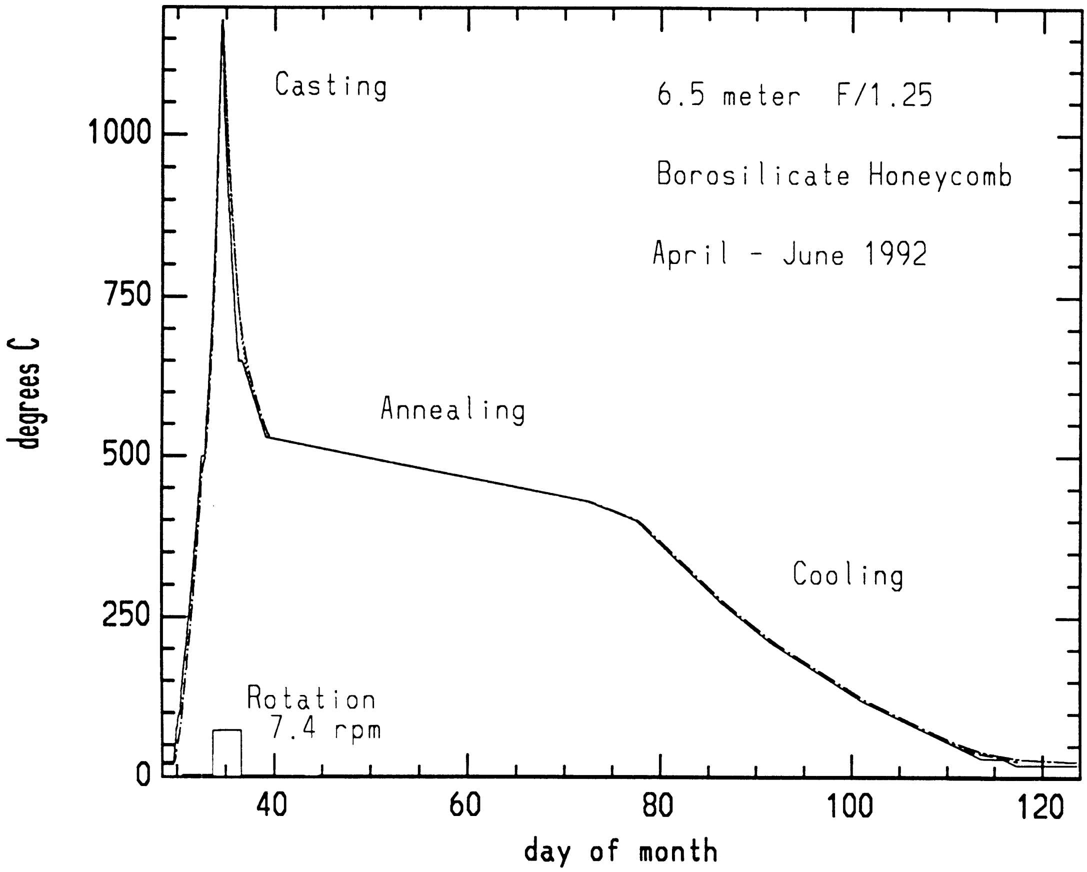

Figure 8: This plot shows the temperature profile of the oven air as well as the temperature of the inside of the mold for the entire casting cycle. The annealing range from 530 to 430 °C was traversed at 3 °C per day.

6.5 and 8.4 meters. The stiffness and short thermal response time of these mirror blanks will improve the achievable image quality of large ground-based telescopes.

Acknowledgements

The credit for the successful casting of the 6.5m mirror truly belongs to a group of dedicated Steward Observatory and MMTO employees. We would specifically like to thank the following people for their contributions to this casting: Eric Anderson, Curt Blair, Karl Buckendahl, Jan Collins, Mitch Collum, Richard Cromwell, Warren Davison, Scott DeRigne, Ken Duffek, Robert Esterline, Elena Ewing, Patty Freimark, Greg Hagedon, David Harvey, Bruce Hille, Stephen Hinman, Mark Hunten, Greg Johnson, Karen Kenagy, Alan Koski, Richard Kraff, Randy Lutz, Sandy Mashburn, John Mathews, Mike Mazzola, Barry McClendon, Robert Meeks, Vince Moreno, Robert Nagel, Blain Olbert, Bill Omann, Ted Parvu, Bruce Phillips, Jeff Rill, Skip Schaller, Erv Smith, Russ Stenman, Wally Stoss, Tom Trebisky, Doris Tucker, Dan Watson, Russ Warner, Steve Warner

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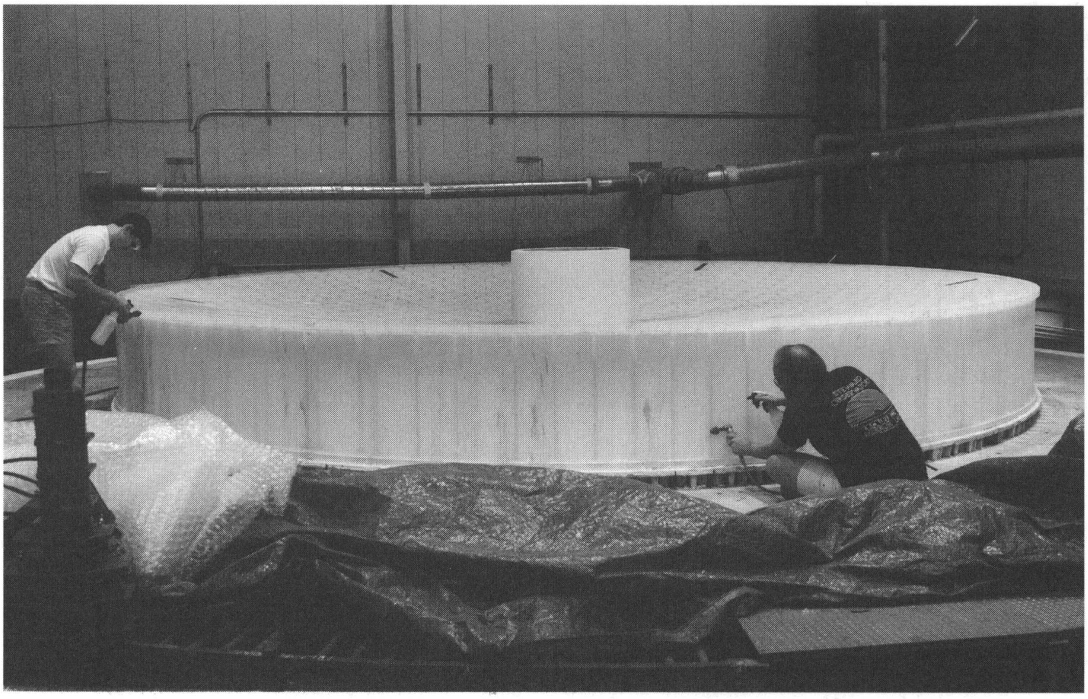

Figure 9: This photo shows the completed mirror after the shell of the furnace was lifted off on June 29, 1992. UA photo by Lori Stiles

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