Casting the first 8.4 meter borosilicate honeycomb mirror for the Large Binocular Telescope

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ABSTRACT

We report on the casting of the first 8.4 meter diameter borosilicate honeycomb mirror at the Steward Observatory Mirror Laboratory. This blank will become the world's largest monolithic glass telescope mirror, and is the first of two mirrors for the Large Binocular Telescope Project. The honeycomb 8.4 meter mirror was cast from 21 tons of E6 borosilicate glass manufactured by Ohara. This glass is melted into a mold constructed of aluminosilicate fiber to produce a honeycomb structure with roughly 20% of solid density. The 1662 hexagonal voids that form the honeycomb structure are produced by ceramic fiber boxes bolted to the bottom of the mold with SiC bolts. The furnace rotates at 6.8 rpm during the casting process to produce the F/1.14 paraboloid on the front surface. This shaping minimizes the amount of glass which must be removed during the grinding process. The front faceplate of the mirror will be 28 mm thick after generating and the back faceplate will be 25 mm. The overall thickness of the finished honeycomb blank is 89 cm at the outer edge and 44 cm at the central hole. The first 8.4 meter mirror blank was cast in January 1997. During the casting, two tons of glass leaked from the mold inside the spinning furnace. After a three month annealing cycle the furnace was opened for inspection. As a result of the leakage about 2 square meters of the faceplate near one edge of the mirror was too thin to be polished. In April 1997, an additional two tons of glass was loaded on top of the intact honeycomb structure. In June 1997, after heating slowly back to the annealing temperature, this extra glass was flash melted onto the front of the blank to assure that the faceplate was of sufficient thickness. After a further three month annealing cycle, the furnace was re-opened to reveal a superb casting with low bubble content and little trace of the fusion boundary. The blank has been removed from the furnace using a fixture glued to the upper surface of the blank. It will soon be stripped of its mold material in preparation for polishing.

Keywords: borosilicate, honeycomb, primary mirror, telescope

1. INTRODUCTION

The Large Binocular Telescope (LBT) Project is constructing a binocular telescope with two 8.4 meter primary mirrors on a common mounting. Those mirrors provide a collecting area equivalent to an 11.8 meter circular aperture plus a diffraction baseline of 22.8 meters. The F/1.14 focal ratio of the parabolic primary mirrors allows the construction of a relatively compact telescope structure and enclosure. Additional details of the telescope are described by Hill & Salinari (1998).

This paper deals with the design and fabrication of the borosilicate glass honeycomb substrates for the primary mirrors which are being fabricated at the University of Arizona's Steward Observatory Mirror Laboratory. Clearly these blanks are a critical technology for the whole telescope. They contribute to the telescope design because of their light weight, their high stiffness and their low coefficient of thermal expansion. The ability to circulate air through the honeycomb structure allows us to control local seeing in the telescope environment.

The Mirror Lab has previously produced three 3.5 meter mirrors, which are now operating successfully in telescopes, and two 6.5 meter mirror blanks. The optical finishing of the first 6.5 meter mirror is reported by Martin *et al.* (1998a). This mirror is now being integrated into the telescope cell as reported by Martin *et al.* (1998b) and should be operating in the converted MMT on Mt. Hopkins in 1999. Both of these 6.5 meter mirrors and the LBT

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8.4 meter mirrors will be supported by active pneumatic supports as described by Gray *et al.* (1994). The designs of the support systems for holding the 8.4 meter mirrors in the furnace, in the handling fixture and in the telescope are summarized by Parodi *et al.* (1996).

2. MOLD ASSEMBLY

2.1. Dimensions

The finished diameter of the 8.4 meter honeycomb mirror blanks for LBT is 8.417 meters with an optical aperture covering 8.408 meters. The central hole diameter is 0.889 meters with an optical aperture of 0.898 meters. The finished faceplate thickness is 28 mm. Both the faceplate diameter and thickness are cast with a 10 mm margin to be removed during generation. The finished backplate thickness is 25 mm, and the ribs are cast to a thickness of 12 mm. The outer edge thickness of the blank is 894 mm, while the inner edge thickness is only 437 mm. The 457 mm sag in the paraboloidal surface is a result of the 9.600 meter focal length (F/1.142). The pattern of the honeycomb ribs is shown in Fig. 1. Unlike previous mirrors, the transition from the regular hexagon pattern to the circular edge of the mirror occurs over three rows of cores. Each of the irregular core shapes at the edge was optimized for minimum stress of the core bottom under the flotation force and for minimum deflection of the faceplate under polishing pressure. Having approximately uniform sizes of these irregular cores also aids in the fabrication of the mold. The finished weight of the mirror blank is 16 metric tons. The honeycomb structure is slightly over 20% of the density of solid glass. The honeycomb structure provides a stiffness an order of magnitude greater than the meniscus blanks used in other telescopes, while the weight is some 40% less.

2.2. Process and Materials

The glass honeycomb sandwich structure is formed by melting chunks of borosilicate glass into a mold which is the negative of the desired structure. The procedure used for mold assembly and casting was essentially the same as that described by Olbert *et al.* (1994) for the 6.5 meter mirrors. A large cylindrical tub is assembled to contain the entire mold under the hydrostatic pressure of the liquid glass. The 48 segments of the tub wall are made from Carborundum *Carbofrax* SiC-based castable refractory. They are restrained by bands of *Inconel 601* which wrap around the tub 90 degrees and connect to pneumatic cylinders outside the furnace. The pneumatic cylinders constrain the tub against hydrostatic pressure during casting, but can be relaxed to avoid stressing the honeycomb blank during cooling. The tub walls and the restraining bands can be seen in Figs. 2 and 3. The 8.4 meter mold uses a total of 124 bands with a cross section of 12.9 square centimeters each.

The base of the mold is assembled from a grid of SiC basetiles which correspond to the position of the honeycomb cores. Each basetile has a SiC nut below it which holds the SiC bolt used to hold the core molds from floating. The basetiles can be seen attached to the bottom of the mirror in Figs. 3, 6 and 7. The injection molded SiC bolts and nuts used to hold down the core boxes are manufactured by Ferro Corporation.

The tub and basetiles are lined with aluminosilicate refractory fiberboard to avoid chemical reactions between the SiC and the molten glass. The 8.4 meter mold has 1662 ceramic fiber core boxes which form the voids in the honeycomb structure. Each of these core boxes is manufactured by Rex Roto Corporation and then machined to its final shape at the Mirror Lab. The installation of the last few cores is shown in Fig. 2.. The removable work platform is used to access the mold during mold assembly and glass loading. The cores must be friable so that they can be removed from the honeycomb structure, yet they must also have the strength and toughness to resist the hydrostatic and thermal stresses during the casting process. Olbert & Schenck (1997) report on several studies of the material properties of this particular ceramic fiber formulation. After the SiC bolt has been tightened to hold each core to the bottom of the mold, stabilizing cross pins are installed to prevent the cores from leaning to the side during the casting. Finally a lid is glued and pinned onto the top of each core box.

2.3. Borosilicate Glass

Glass in general is used for mirror substrates because it is extremely stable and it polishes well at the nanometer scale. Borosilicate glass is used for the production of these mirrors because it is relatively inexpensive and it can be readily cast into the desired honeycomb structure. We use the particular borosilicate, E6, made by Ohara Incorporated in Kanagawa, Japan. E6 is a good match to our process because it is manufactured in appropriate volumes with good quality control, and because the broken surfaces of the chunks melt together smoothly without discontinuities.

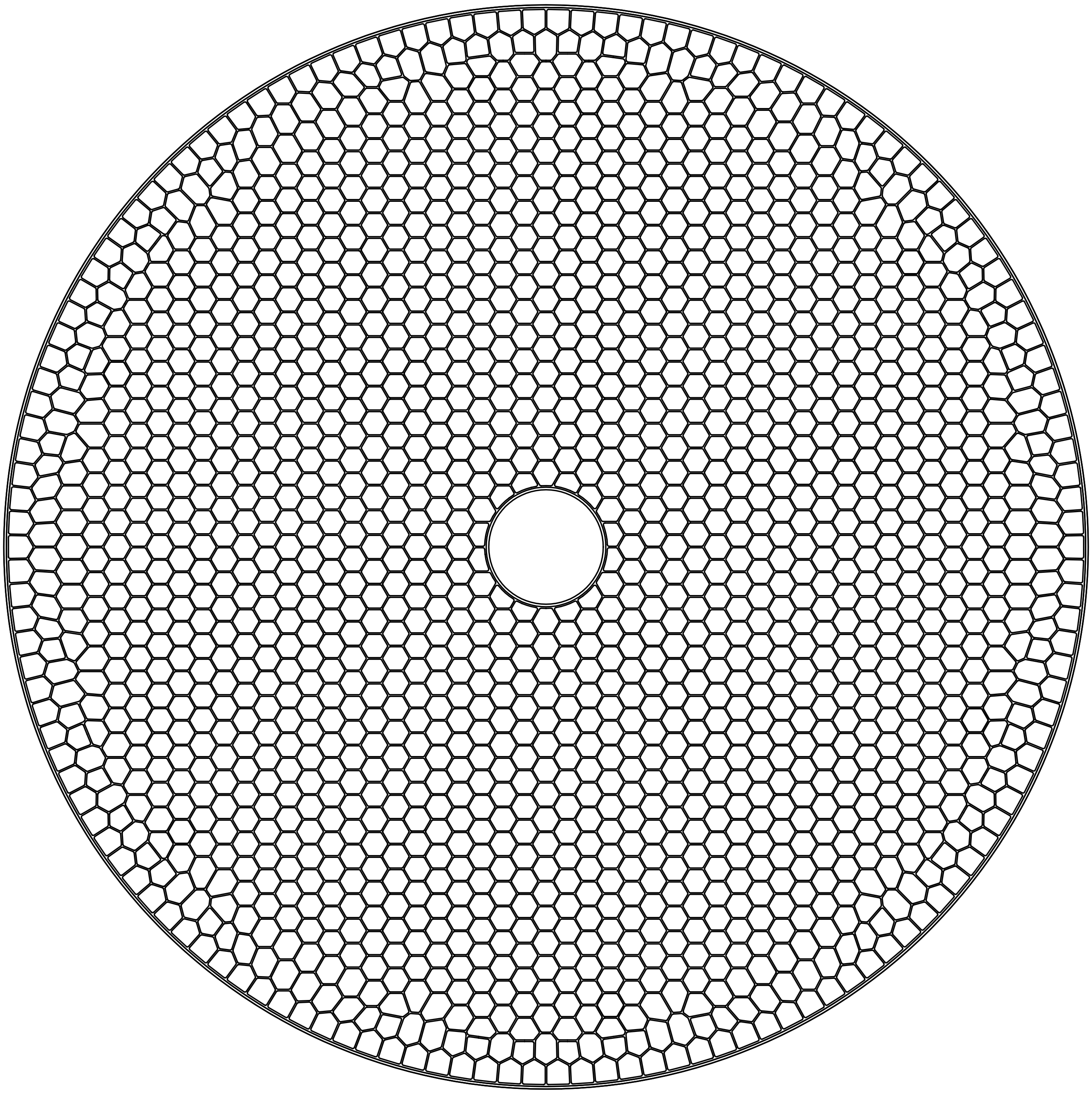

Figure 1. This figure shows the pattern of honeycomb ribs for the 8.4 meter mirror. Each of the ribs is 12 mm thick. Steward Observatory drawing.

Figure 2. This figure shows Dan Watson installing of one of the last ceramic fiber core boxes.

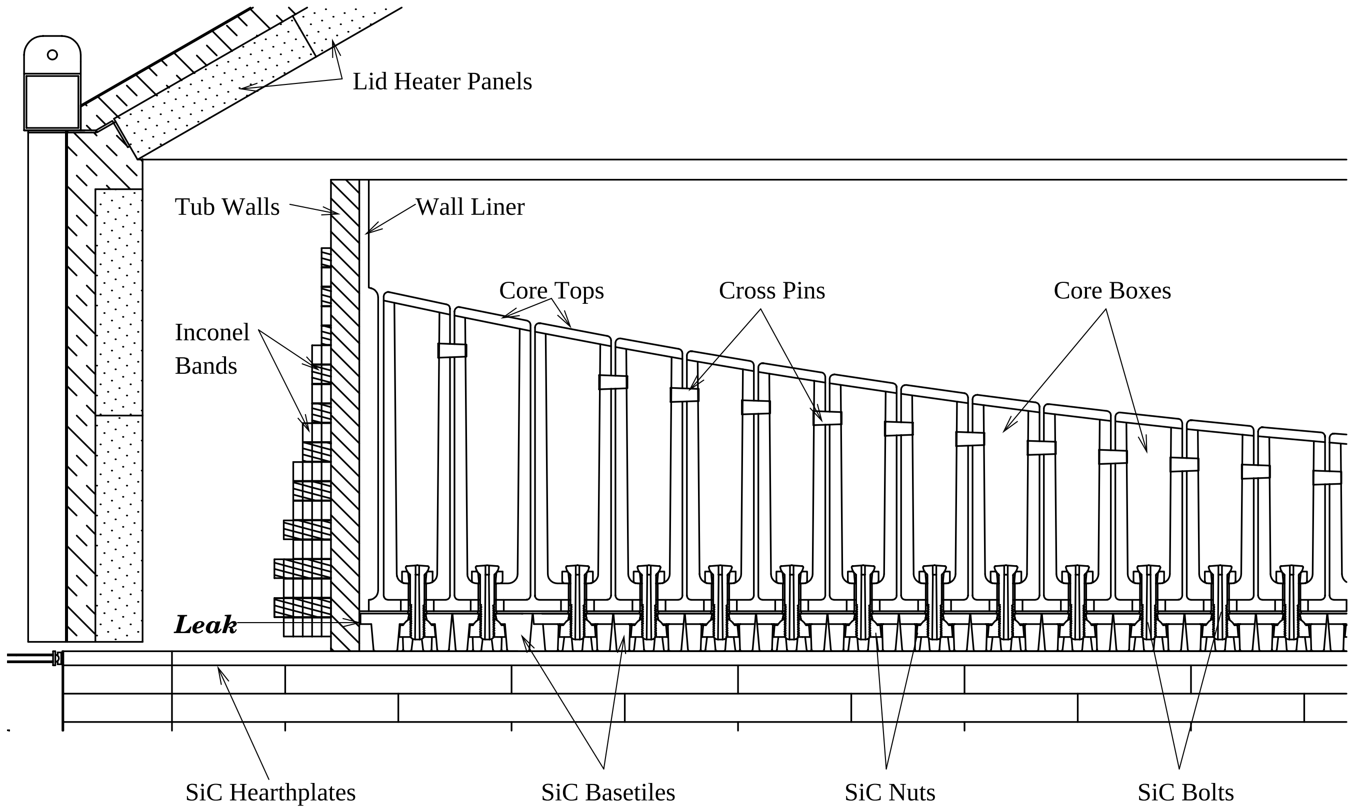

Figure 3. This figure shows a cross-section of the mold for the 8.4 meter mirror. Glass chunks are piled directly on top of the cores before the casting process begins. Steward Observatory drawing by Eric Anderson.

3. CASTING

Twenty-one tons of glass were carefully loaded onto the mold and the furnace lid was lowered into place. The heating cycle was started on January 12, 1997. Rotation at 6.8 RPM was begun when the furnace reached 750 $°C$ on the morning of January 18. Spinning and heating continued through the night until we reached the maximum temperature of 1180 $°C$. We started cooling after only two hours at high temperature because the on-board video cameras indicated that the level of the glass was dropping more than expected. Based on the glass dropping below the calculated level mark on the full mold, we deduced that there must have been a significant glass leak. Since the video cameras only cover a portion of the furnace, the leak was not visible. Because we could see that there was an 8.4 meter honeycomb structure, the mirror blank was given a normal cooling and annealing cycle for the next three months. While we had various speculations about the leak and estimates of the faceplate thickness, the exact nature of the leak was not revealed until we opened the furnace on April 2, 1997.

A number of leaks at the base of the tub wall sections allowed approximately two tons of glass to flow out of the mold and onto the SiC hearthplates in the gap between the tub walls and the outer walls of the furnace. The result was that most of the mirror had a faceplate thickness in the range of 20 - 32 mm; this would be thick enough to polish. However about 4% of the surface in a patch near the edge was too thin to polish.

With engineering hindsight we have determined that we did not apply sufficient tension to the Inconel band system to assure that the tub could resist the forces that try to push it apart. Our analysis had included the hydrostatic pressure of the molten glass, the centripetal forces from rotation and the friction of the restraining bands against the tub walls. We had neglected the friction of the interwoven sets of bands rubbing on each other as the entire mold expands. Each set of bands enters the furnace wall and wraps 90 degrees around the tub before exiting on the far side of the furnace. The result is four interwoven sets of bands constraining the tub. The band-band friction between these interwoven sets reduced the effective tension in the bands to the point where they could no longer constrain

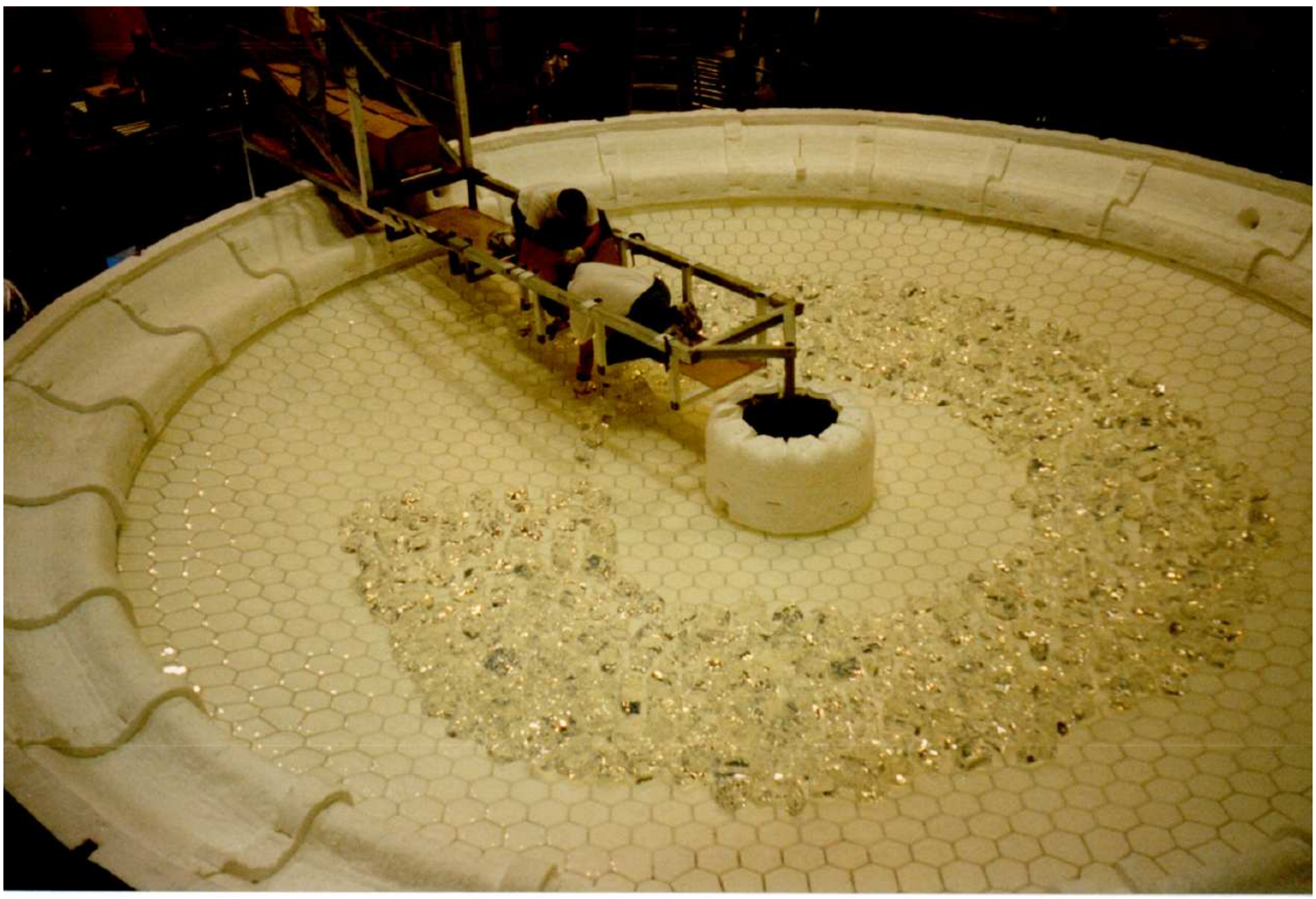

Figure 4. Two tons of additional glass being placed on the 8.4 meter mirror blank before the remelt to repair the faceplate. During the remelt this glass flowed across the entire faceplate to increase the thickness to 40 mm. Kaowool insulation is covering both the inner and outer tub walls.

the tub walls. Based on the viscosity of the glass, we have deduced that the worst leak occurred where the bottom of two wall sections pushed out from the basetiles by 18 mm. Since the loss of tension in the bands is caused by friction when the tub expands, the effect reverses as soon as the tub starts to contract. Once we started to cool the furnace, the tub walls were pulled back into place while the glass was still molten.

4. REMELTING

Faced with the prospect of having, forever, a mirror blank with 4% of its surface unuseable, we were highly motivated to invent a solution to repair the faceplate. The adopted approach was to add two tons of additional glass on top of the existing honeycomb structure. To avoid additional leaks and other possible damage to the honeycomb structure, we elected to do the remelt in "broil" mode where heat was only applied from the top side of the mold. The two tons of new glass chunks can be seen in Fig. 4. The challenge of this remelting process was not getting the new glass to adhere to the surface, but rather to add the new glass without creating a devitrified layer at the bond line or deeper in the honeycomb structure. The main body of the blank was slowly heated up to 650 $^{\circ}C$ during the month of May. By heating the honeycomb structure to near the softening point, we protect it from possible damage during the remelt, but still keep its viscosity high enough to avoid additional leakage. Then the lid heaters were turned on at maximum power to melt the chunks of glass onto the faceplate. This remelting occurred on June 10, 1997. A video view of the "thin" portion of the faceplate is shown before and after the remelting process in Fig. 5. The inner and outer tub walls were covered with a layer of Kaowool insulation to protect them from the thermal load of the heaters. That insulation can be seen in Fig. 4 and at both the top and the bottom of Fig. 5.

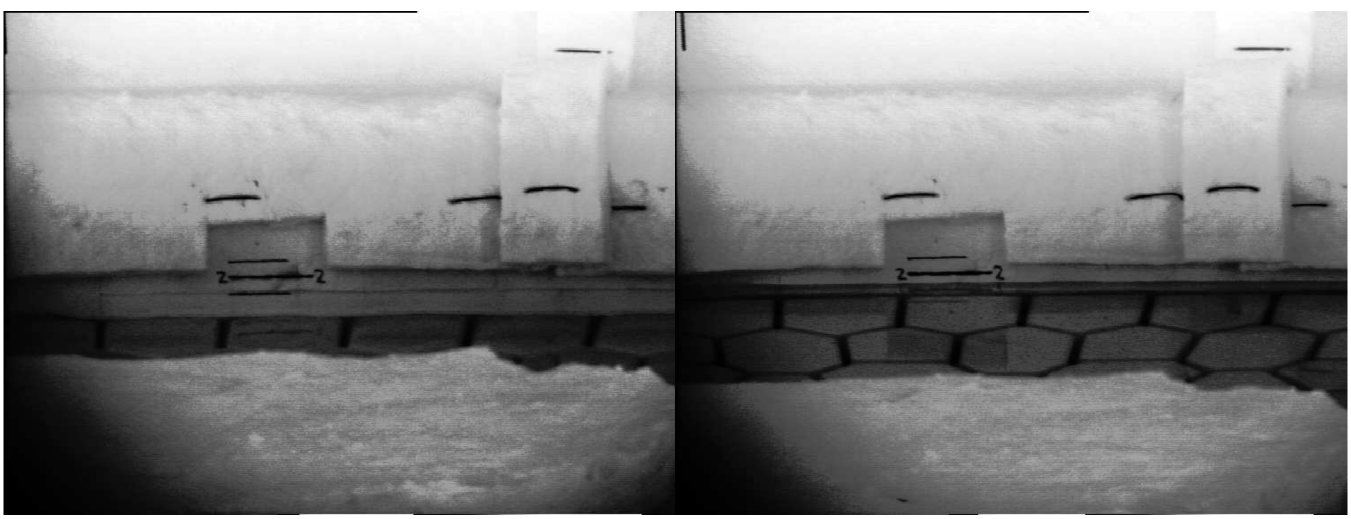

Figure 5. Before (left) and after (right) images of the faceplate remelting as seen by a camera looking across the furnace. This camera was installed after the original casting specifically to monitor the remelting process. The marks on the tub wall represent inches of faceplate depth. The glass appears dark in these images taken with a strobe through a blue filter.

5. RESULTS

On September 12, 1997, the lid of the furnace was removed to reveal a complete 8.4 meter honeycomb mirror blank with a full thickness (40 mm) faceplate. The bonding of the remelted glass to the existing faceplate was a complete success. There are just a few tiny bubbles resulting from dust at the bond line. In fact, this has turned out to be the nicest faceplate the Mirror Lab has ever produced from the cosmetic point of view. In the following weeks the walls of the furnace were removed and the leaked glass was mined from the floor of the furnace. When the hot glass contacts the SiC parts of the mold it reacts and forms CO_2 bubbles so the result is a frothy glass resembling pumice. Fortunately this foamed glass does not stick very well to the SiC hearthplates or basetiles. The Inconel bands and tub walls were also removed to reveal the sides of the blank. The exposed blank still with the honeycomb cores inside is shown in Fig. 6.

The 8.4 meter blank was lifted off the furnace on February 23, 1998. The back of the mirror in the vertical position is shown in Fig. 7. Additional details about the lifting and handling of these large honeycomb mirrors are provided by Davison, Williams & Hill (1998). The mirror now resides in the cleanout station while the core molds are being removed with high pressure water spray. Once the cores have been removed and the blank has been inspected, the 8.4 meter mirror will be stored in the cleanout station until generating and polishing can begin.

6. CONCLUSION

The Steward Observatory Mirror Laboratory has successfully cast the world's first 8.4 meter diameter borosilicate honeycomb mirror. This casting of the world's largest monolithic mirror blank represents the culmination of a research and development project started back in 1980. The first 8.4 meter mirror is expected to see first light in the Large Binocular Telescope in 2002 after polishing and construction of the telescope have been completed. In 1998 a third 6.5 meter mirror is to be cast with a second 8.4 meter blank for LBT to be undertaken the following year. Up to date information about the Steward Observatory Mirror Lab can be found on the world wide web at URL `http://medusa.as.arizona.edu/mlab/mlab.html` .

ACKNOWLEDGEMENTS

Clearly the authors of this paper were not alone in their efforts to cast an 8.4 meter mirror. A great deal of credit must go to the staff of the Mirror Lab and to the Steward Observatory Technical Division for their work to make the project a success. Particular credit goes to Randy Lutz, Dan Watson, Carl Anderson, Rex Barrick, Ned Franz, Phil Muir and Bruce Phillips for their extended tour of oven pilot duty watching the mirror 24 hours a day over seven months. This work was funded by the Large Binocular Telescope Corporation.

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Figure 6. The completed 8.4 meter mirror blank on the furnace with a few friends assembled from the staff and students of Steward Observatory. This honeycomb mirror blank represents the world's largest monolithic piece of telescope glass. Photo by Lori Stiles and John Florence.

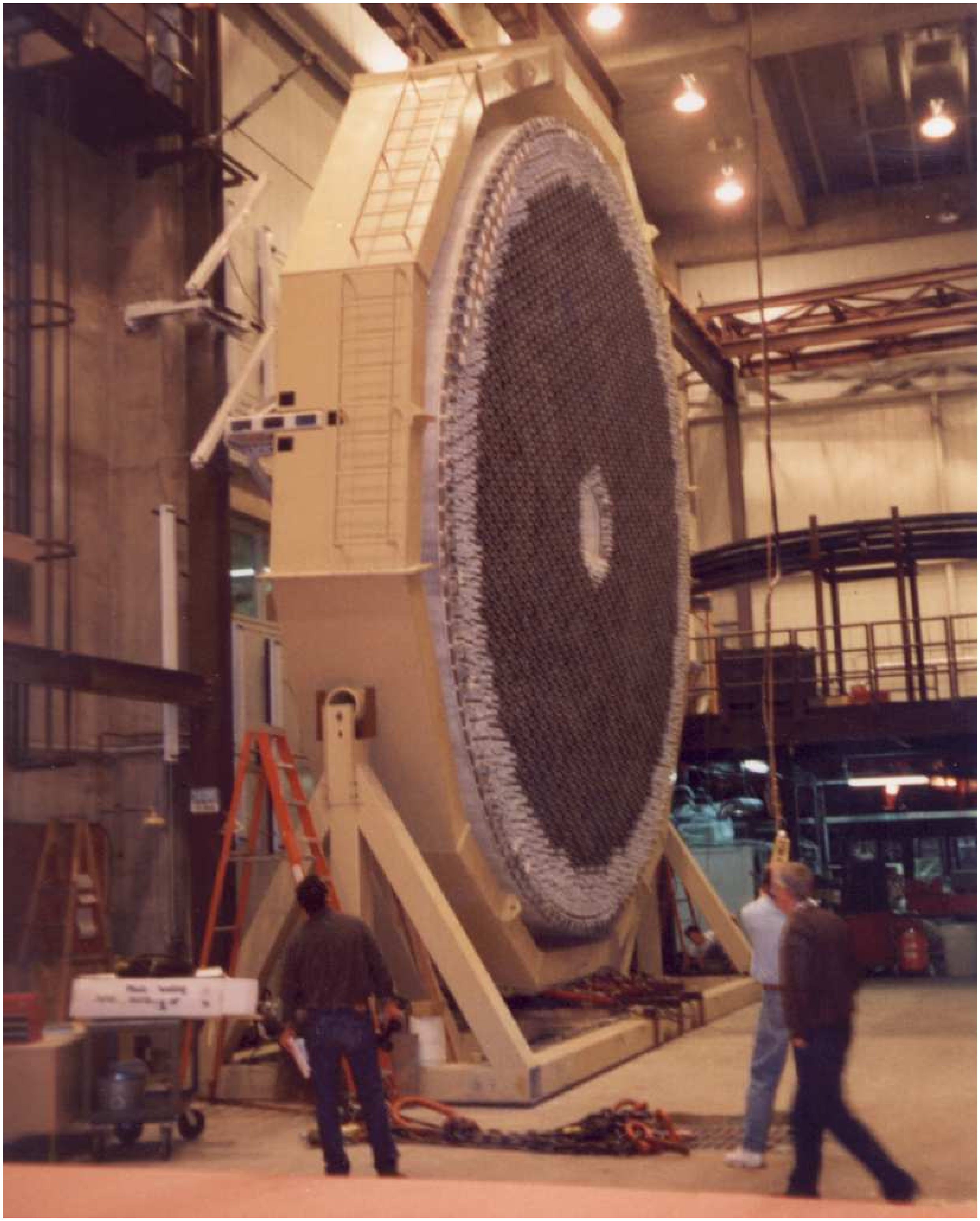

Figure 7. The 8.4 meter mirror blank in the vertical position in preparation for mold removal. The SiC nuts and basetiles can be seen attached to the backplate of the mirror.