30 years of mirror making at the Richard F. Caris Mirror Lab

Buddy Martin[a], John Hill[b] and Dae Wook Kim[a, c, *]
[a]*Steward Observatory, University of Arizona, Tucson, AZ 85721, USA*
[b]*Large Binocular Telescope Observatory, 933 North Cherry Avenue, Tucson, AZ 85721 USA*
[c]*College of Optical Sciences, University of Arizona, Tucson, AZ 85721, USA*

**letter2dwk@hotmail.com*

Abstract: The Richard F. Caris Mirror Lab at the University of Arizona has made lightweight honeycomb mirrors for some of the world's largest telescopes. Its 30 years of mirror making history, enabling a series iconic telescopes, is presented.
OCIS codes: (000.2850) History; (110.6770) Telescopes; (350.1260) Astronomical optics

1. Purpose of the Mirror Lab

The Richard F. Caris Mirror Lab is part of the Astronomy Department at the University of Arizona. It was built to make telescope mirrors that offer superior performance and that could not be obtained commercially. The primary advantage of these mirrors is their lightweight honeycomb structure with a mass only 1/5 that of a sold mirror of the same dimensions. These mirrors hold their shape under forces of gravity and wind, and minimize thermal effects by closely following the changing air temperature. A number of large telescopes have been designed to use the honeycomb mirrors. The Mirror Lab's ability to supply them makes it possible for the university to be a partner in some of the world's most powerful telescopes, including the 2 × 8.4 m Large Binocular Telescope (LBT) [1] and the 25 m Giant Magellan Telescope (GMT) [2].

2. Early history

Starting in the late 1970s, Roger Angel and colleagues at the University of Arizona's Steward Observatory envisioned a way to break through the 5 m barrier for high-performance mirrors for optical telescopes. At the time, the largest telescope mirror that delivered excellent images was the 200 inch mirror of the Hale Telescope at Palomar Observatory, a mirror that was cast in 1934 and saw first light in the telescope in 1948. Designing a larger mirror that would maintain excellent performance was a tremendous challenge primarily because of the mechanical deformation under its weight and the thermal deformation under the temperature gradients that arise as the ambient air changes temperature. Angel's solution was to make a lightweighted mirror out of borosilicate glass, following the general concept of the 200 inch mirror but adding a backsheet for stiffness and increasing the lightweighting from a factor of 2 to a factor of 5.

Angel and John Hill started experimenting with casting borosilicate into complex molds around 1980. In 1981 they cast a 60 cm mirror with a design and method that could be scaled up to much larger diameter. The general method was to fill the mold with square boxes (later hexagonal) of insulating concrete (later ceramic fiber) to form the voids in the honeycomb mirror. Solid chunks of glass were laid on top of the boxes, the mold was heated to 1200°C in an electric furnace, and the molten glass flowed around the boxes to fill the mold and form the honeycomb structure. The mirror blank was then cooled slowly to anneal. This method led to two successful 1.8 m honeycomb mirrors by 1983.

Angel saw that future telescopes in the 8 m class would benefit from short focal lengths in order to make them stiffer and make them fit in smaller, less expensive domes. Angel, Hill and Larry Goble led an effort to cast a 1.8 m f/1 paraboloid in a spinning furnace so the centrifugal force would produce roughly the desired parabolic surface. Spin-casting would be an important development for 8 m class mirrors because it would eliminate the need to grind away many tons of glass from a stationary casting. The 2 m furnace was mounted on a re-purposed telescope bearing in a former synagogue on the University of Arizona campus. The mold and mirror designs were by then mature and have hardly changed since this first spin-cast mirror. The glass was E6 borosilicate from Ohara Corporation. The mold was made of alumina silica ceramic fiber. Figure 1 shows the design of this mirror, with hexagonal cavities at 19.2 cm spacing, glass ribs 19 mm thick (reduced to 13 mm in later mirrors) between cavities, a 25 mm backsheet and 28 mm facesheet. The mirror was cast in March 1985.

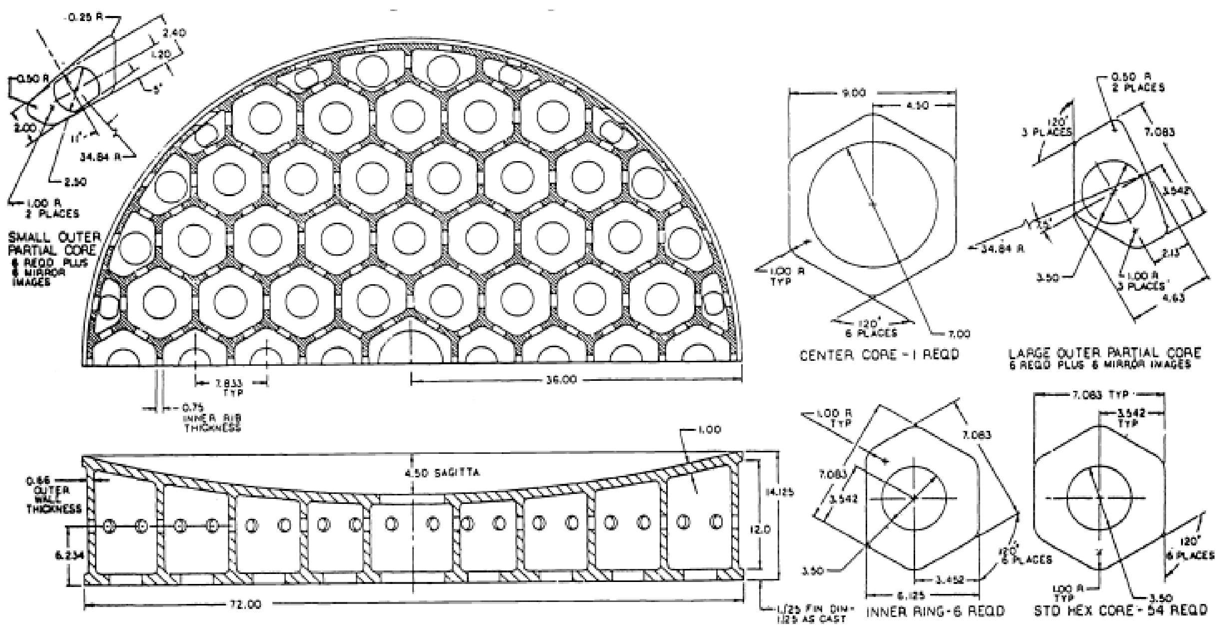

Fig. 1. Dimensions in inches of the first spin-cast mirror at the University of Arizona.

3. Development of the present Mirror Lab

The successful spin-casting of the 1.8 m mirror demonstrated that there were no fundamental issues that would prevent casting much larger mirrors. Angel and colleagues immediately set out to create a facility to make 8 m mirrors. The university provided space under the east stands of Arizona Stadium. The new Steward Observatory Mirror Lab was built in 1985 and 1986, using the concrete columns of the stadium for support and filling in walls, a ceiling, and a smooth concrete floor. The first major piece of equipment, still the dominant item at the Mirror Lab, was the 12 m turntable that would support a furnace large enough to cast 8 m mirrors. It sits on a crossed roller bearing and has slip rings that supply up to 2 MW of power to heat the furnace and transmit data to and from on-board computers.

The initial furnace was 6 m in diameter with a plan to cast several 3.5 m mirrors before expanding the furnace to 8 m capacity. The first casting, in 1987, was a 1.2 m mirror that became the primary mirror for a telescope at the Smithsonian Astrophysical Observatory. It was followed by a series of 3.5 m mirrors that later went into telescopes operated by the Astrophysical Research Consortium (cast in 1988), the Wisconsin-Indiana-Yale-NOAO consortium (1988), and the US Air Force (1989).

In parallel with the spin-casting development, Angel and colleagues were developing a method of polishing the extremely aspheric surfaces of mirrors as fast as f/1. Known as stressed lap polishing, it uses a stiff disk whose shape is controlled by actuators that apply bending moments, making the lap's polishing surface match the local shape of the mirror at all times. The method was used initially for the 1.8 m f/1 mirror, in a small polishing shop built inside the Mirror Lab. This mirror would become the primary mirror for the Lennon Telescope on Mt. Graham in southern Arizona.

4. Expansion

Up to this point the development of casting and polishing technology had been funded primarily by the National Science Foundation and the University of Arizona. The Mirror Lab then received substantial funding from the US Air Force to polish one of the 3.5 m mirrors for a telescope at the Starfire Optical Range. This allowed the lab to expand in 1990 with a dedicated polishing lab as well as office space. The 8.4 m capacity Large Optical Generator was moved from the Optical Sciences Center to the Mirror Lab and became the machine for both generating and polishing large mirrors. A 24 m test tower was installed with the aim of measuring 8 m mirrors. This facility was used to polish the Air Force 3.5 m mirror and then to finish the other 3.5 m mirrors whose polishing had been started at other facilities. In 2003 an 8.4 m polishing machine was installed in the polishing lab, giving the Mirror Lab a second station for grinding and polishing mirrors. Later expansions of the lab provided space to assemble mirror support cells and to integrate mirrors with their cells.

Following the 3.5 m castings, the furnace was enlarged to cast a 6.5 m mirror that would replace the six 1.8 m mirrors of the Multiple Mirror Telescope on Mt. Hopkins, Arizona. The MMT mirror was cast in 1992 and its polishing was completed in 1997. The next four castings alternated between 6.5 m mirrors cast in 1994 and 1998 for the twin Magellan telescopes at Las Campanas Observatory in Chile, and 8.4 m mirrors cast in 1997 and 2000 for the LBT on Mt. Graham. After a remarkable series of castings with so serious problems, the first 8.4 m casting was a reminder of the risks of scaling up processes that had been proven at smaller scales. The additional stresses and constraints on the mold created small leaks in the tub wall, allowing some 2 tons of liquid glass to escape and leaving too little glass in the facesheet of the mirror. The Mirror Lab's scientists and engineers went through a period of analysis and tests to develop a rescue plan, which consisted of adding new glass on top of the existing mirror blank, and heating only the top portion of the furnace to fuse the new glass with the original. This effort was successful at producing a mirror blank with no remnant of the leakage.

5. Current status

As of 2016 the Mirror Lab has cast five 6.5 m mirrors and seven 8.4 m mirrors. The most recent 8.4 m mirrors include the first four of eight segments for the primary mirror of the GMT to be built at Las Campanas, as well as the combined 8.4 m primary and 5.0 m tertiary mirrors for the Large Synoptic Survey Telescope (two concentric mirror surfaces on one glass substrate). Seven of the GMT mirror segments are off-axis parabolic mirrors that present major challenges, especially in the requirements for optical tests. In 2006 the Mirror Lab replaced the test tower with a larger, 28 m tower that houses a set of four systems that provide independent measurements of the GMT segments. The first off-axis GMT segment was polished to completion in 2012.

In 2015 the Mirror Lab was renamed the Richard F. Caris Mirror Lab to acknowledge Mr. Caris's contributions to the University of Arizona and especially to the university's participation in the GMT. Thirty years after construction of the original Mirror Lab, the lab continues to develop innovative technology for fabrication and testing of the world's largest mirrors [3-6].

6. References

[1] J. M. Hill, et al., "The Large Binocular Telescope: binocular all the time", Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 914502 (2014).

[2] R. A. Bernstein, et al., "Overview and status of the Giant Magellan Telescope project", Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 91451C (2014).

[3] H. M. Martin, et al., "Production of primary mirror segments for the Giant Magellan Telescope", Proc. SPIE 9151, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, 91510J (2014).

[4] H. M. Martin, et al., "Manufacture and final tests of the LSST monolithic primary/tertiary mirror," Proc. SPIE 9912, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II, 99120X (2016).

[5] Dae Wook Kim, et al., "New and improved technology for manufacture of GMT primary mirror segments," Proc. SPIE 9912, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II, 99120P (2016).

[6] H. M. Martin, et al., "Status of mirror segment production for the Giant Magellan Telescope," Proc. SPIE 9912, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II, 99120V (2016).