8 m BOROSILICATE HONEYCOMB MIRRORS

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ABSTRACT

The largest existing telescope mirrors, the Palomar 5 m and Soviet 6 m, are made of borosilicate glass. The same glass, because of its relative ease of manufacture, is a good candidate for 8 m mirrors. At this size, considerations of stiffness, weight and thermal response strongly favor honeycomb sandwich design. Taking mirror image quality of 1/8 arc second as a target, we find the optimum design has hexagonal honeycomb cells 200 mm across and 600 mm deep, sandwiched between faceplates 25 mm thick. The mirror will weigh 14 tons. Analysis and experiment show excellent stiffness against the deflecting forces of gravity, wind and polishing tools. Thermal response is rapid, so that image degradation from mirror seeing and internal thermal gradients can be avoided by ventilation of the honeycomb cells. Mirrors of this design should not need active correction of their figure, and will thus be economical to operate.

A method to make honeycomb sandwich mirrors has been developed, casting in one piece in a complex mold. The furnace spins while the glass is liquid to form the curved face of the mirror. Following tests at the 1.8 m size, a facility for casting 8 m mirrors has been constructed, with a 12 m diameter turntable. It supports presently a 6 m diameter furnace, made from parts that will be incorporated into the full size version. The first blank at 3.5 m diameter has just been cast. One or two more of these and a trial 6.5 m casting will be made before the first trial at the full 8 m size.

1. INTRODUCTION

The arguments for building a new generation of larger ground-based telescopes for optical and infrared wavelengths are well known. Research opportunities are great and there is hope that diffraction limited imaging may be realized by the use of adaptive optics to overcome atmospheric blurring. Based on considerations of imaging and handling, the optimum diameter for individual mirrors in single and array telescopes is around 8 m (Angel and Woolf, 1983). However, the desired performance and economy cannot be achieved simply by scaling up present 4 m telescope designs. The new mirrors must not only be larger than before, but also give better image quality.

One might suppose that, if auxiliary optics to correct for atmospheric and other aberrations become commonplace, then optical tolerances could be relaxed. However adaptive optics are complex, and need pupil re-imaging optics or special secondaries. Given the variety of optical configurations envisaged for each telescope, reliance on adaptive correctors would be restrictive and expensive. Thus, we must ensure that wavefront degradations caused by telescope aberrations are less than those caused by the atmosphere under conditions of excellent seeing.

The best images recorded from the ground have a resolution of around 1/3 arc second. If the large telescopes are ever to match this performance, their contribution to image blurring should be no more than 1/4 arc second. Allowing for optical aberrations, tracking errors and so on, we should only allow the primary mirror alone to contribute an error of about 1/8 arc second. Since several different sources of aberration contribute to this, each can only be allowed about 1/16 or .06, arc seconds. This is a criterion which we will apply uniformly to the different sources of large scale errors discussed below. Small scale errors cannot be treated in this way. As discussed in section 2 below, such errors scatter light into a halo whose angular size depends on their spatial frequency and whose brightness depends on their amplitude. Detailed specifications are best set with reference to a structure function, that gives an amplitude tolerance on each scale (Angel, 1987).

The mirrors in today's major telescopes do have the dimensional stability needed for the desired imaging quality. They are made of glass, which has exceptional long term stability, and once correctly figured holds its shape for decades. Mechanical stability in all cases requires the mirror to be supported in "floatation", that is by a system to counter the force of gravity locally with many distributed force actuators. In this way bending moments set up by gravity are reduced to insignificant proportions, regardless of orientation. Typically thicknesses of 40 cm have been used in 4 m mirrors, to be sure of sufficient rigidity, and giving masses of around twelve tons. Thermal figure stability in these mirrors then requires the use of glass with very low expansion coefficient. This is because, as the temperature changes, the thick glass with low thermal diffusivity inevitably develops significant internal thermal gradients, typically of a degree or more.

Despite the care taken to preserve an accurate reflecting surface, current 4 m mirrors will often significantly distort the incoming wavefront, because of mirror seeing. The same high mass used to get stiffness results in high thermal inertia, and convection currents above the mirror surface cause refractive aberrations larger than any in reflection. Most of the time they will be worse than the 0.06 arc second goal. (Woolf and Cheng, 1988)

Further difficulties would develop if the current approach were extended from 4 m to 8 m diameter. The mirror becomes more susceptible to errors in support forces, even if the thickness is scaled with the diameter. If the thickness is reduced to bring cost and thermal inertia to acceptable levels, then flexibility may defeat the floatation principle. While even very thin mirrors can always in principle be exactly counterbalanced, huge mirrors act as sails in the wind, and experience unpredictable bending forces, (section 2 below).

I think there would be a widespread agreement that the ideal solution for 8 m telescopes would be to use stiff, light-weighted mirrors of zero expansion glass, with a front faceplate conditioned to follow the night air temperature. Unfortunately, the methods available to make diffraction limited space optics of honeycomb sandwich construction are not well matched for ground-based telescopes which need much bigger mirrors and can tolerate less stringent specifications. The established techniques of making honeycomb core, by bonding together many glass pieces or by hollowing out a solid blank, would be extremely difficult and expensive at the 8 m size. This is why the University of Arizona is undertaking to develop new technology and facilities specifically for casting 8 m honeycomb mirrors.

The plunge into molten glass technology is a departure for astronomers. The growing fashion in telescope design is to compensate for inadequate rigidity with active figure control from imaging servo systems. Our decision to go back to the fundamental substrate issue was shaped in part by the experience of building and operating the MMT, which is the only major operating research telescope to use servo-systems and image monitoring to maintain image integrity. Its six individual rigid primary mirror elements are rigidly connected to a stiff steel structure, and occasional corrections (every 10 minutes) made at the secondaries are used to compensate for thermal and gravitational deformation of the steel. The large research output of the telescope testifies to the success of the engineering effort. In reality though, even as simple a servoed system as this has consumed many man years of hardware and software engineering, and requires the continued reliable operation on the mountain of many sophisticated components. Contrast this with the 5 m Palomar telescope, whose mirror is of borosilicate glass, cast in the form of a rigid ribbed plate. Apart from occasional maintenance of the support counterweights, the mirror simply works. The best images recorded with this telescope are about 0.6 arc seconds, recorded during focus tests (Oke, 1988).

It was our conviction several years ago that the simplicity of the 5 m mirror and its economy of operation could be extended to the 8 m size, even for the higher levels of performance now demanded. The improvements needed are the use of a honeycomb sandwich structure, which is stiffer than a ribbed plate, and of thinner sections to reduce thermal inertia. Now with detailed computations and measurements of the mechanical and thermal properties in hand, and reported elsewhere in these proceedings, borosilicate honeycomb sandwich blanks are proving they can live up to our expectations. Furthermore, with the support of the NSF, much progress has been made in building the facilities needed to cast such blanks. A building, handling facility and furnace turntable for 8 m spin casting are complete, and about half of the 8 m furnace is already constructed and operational. The first test blank at 3.5 m diameter has been cast.

In the same spirit of going to the heart of the current technological limitations, we have also turned to another key problem in scaling up today's telescopes, that of mirror polishing. One would like the 8 m telescopes to be as short as possible, to be stiff and economical. Yet the established polishing methods rely heavily on the mirror being not too far removed from a spherical surface, and take a long time. Thus the parabolic surfaces for optical telescopes have all been of relatively long focal length, f/2 and slower. A new approach is being developed that will allow quicker polishing, and the figuring of the 8 m borosilicate mirrors at f/1.2, with some five times larger departure from a spherical surface than is needed for f/2. This stressed lap method is described in these proceedings by Martin, Angel and Cheng (1988). At present only projects with borosilicate honeycomb mirrors plan to use it, but it is in fact applicable to aspheric mirrors of any type.

In this paper we deal with blank manufacture. Section 2 reviews the rationale for the choice of borosilicate glass and for the current design of the 8 m f/1.2 honeycomb mirrors to be used in the Columbus and Magellan telescopes. Section 3 describes the design of molds to cast honeycomb blanks in one piece, and section 4, the furnace for melting and annealing. The progress to date with experimental castings and mirrors, including the most recent 3.5 m casting, is given in Section 5.

2. HONEYCOMB MATERIAL AND GEOMETRY

Material

The key to making the mirrors at an affordable cost was the realization that borosilicate glass would do the job. Used since its invention to make mirrors as well as laboratory and oven ware (Pyrex), this glass polishes well, has the highest chemical stability, and is of relatively low cost. For us, its overwhelming advantage is that it can readily be melted and cast into molds. As will be described below, molds can be made with such intricacy that a complete honeycomb sandwich structure, with front and back facesheets, can be cast in one piece. We have discovered some new tricks that simplify the casting process, compared to that used to make the Palomar 5 m mirror. For example, mirrors do not have to be poured; the mold can be filled with many blocks of cold glass that are simply melted together. As long as these have pristine surfaces, as when fractured from a pot batch, then the boundaries vanish on melting and an almost completely bubble free blank is produced.

Despite its many advantages, borosilicate glass is commonly viewed with suspicion by astronomers and opticians. The concern stems entirely from the fact that its expansion coefficient is not zero, so mirrors made from it can suffer thermal distortion. However, the low thermal inertia and large surface area of a honeycomb structure make it possible to achieve rather accurate thermal equilibrium in practice. In fact the ventilation system needed to eliminate mirror seeing, by keeping the faceplate in good thermal equilibrium with the air, will serve also to keep internal thermal equilibrium and eliminate figure errors. In these proceedings Cheng and Angel (1988) deal with this topic. A key result is that to keep the reflecting surface within 0.2^{o}C of ambient, and hence mirror seeing $\leq$ 0.06 arc second, the faceplate must both be thin (25 mm) and well ventilated from the back side, where the heat transfer rate must correspond to a good breeze at the front surface (10 W/m^2/K). Heat transferred at similar rates from the other internal surfaces then can ensure internal equilibrium to 0.1^{o}C, and eliminate figure distortion also to the .06 arc second level. Cheng and Angel give experimental results that verify such equilibrium can be achieved at cooling rates typical of mountaintop conditions, and describe practical air supply systems.

Another factor favoring borosilicate glass has been the availability of material of very high quality. Most of our experience has been obtained with E6 borosilicate glass made in Japan by Ohara. This is melted in clay pots, the traditional method of optical glass manufacture, with vigorous stirring that yields high homogeneity and low striae. It is supplied to us in the form of roughly cubical blocks with smooth , uncontaminated fracture surfaces and weighing typically 4 Kg each. The expansion coefficient at 0°C is 2.8×10^{-6}°C and the liquidus temperature about 950°C. Recently Corning has made for us an experimental run of type 7761 glass, in a continuous melter. It comes in the form of "loaves" about 20 cm long. The 1.2 m mirror we have made with the glass is promising, but further work is needed to get surfaces that melt perfectly together, and to get the high homogeneity of the stirred pot melt. For this glass the expansion coefficient is 2.9×10^{-6}/°C and the liquidus temperature about 850°C.

A key parameter for any glass to be used for telescope mirrors is its homogeneity. Any mirror can show distortion, even when completely isothermal, if the glass is not homogeneous in its expansion coefficient. If the operating temperature is different from that at which the surface was figured, there will be a "bimetallic strip" type of distortion. The amount of this distortion depends only on the variation in coefficient of thermal expansion, and not on its absolute value. A mirror that is figured at 20°C and is to be operated at 0°C with no more than 0.06 arc second distortion needs homogeneity of about 10^{-8}/°C, depending on mirror thickness and the spatial scale of variations (Angel et al. 1983). The measured variation from pot to pot (ton to ton) for E6 is $\pm1\times10^{-8}$/°C, and slightly less for the Corning glass over continuous production of several hundred Kg. No better uniformity is achieved in large blanks of very low expansion glasses, such as Zerodur and ULE.

Optimization of the Honeycomb Structure

The thermal requirement, as we have discussed above, is that the sections be thin enough, $\leq$ 25 mm, to give short thermal time constants. The other dimensions of the honeycomb structure must then be determined by consideration of mechanical stiffness. For reasons of manufacture, we prefer to use a hexagonal honeycomb. This gives the mold cores the maximum strength against collapse due to hydrostatic pressure of liquid glass. We also, for reasons of manufacture and support, prefer to make the mirror with a flat back. The resulting plane-concave shape may at first seem awkward, compared to a radio dish. However, because the gravitational load is taken by many load supports, not at a center hub, there turns out in practice to be no significant disadvantage.

The externally applied loads that must be withstood by any mirror are those of wind while in operation, and of the polishing tool during fabrication. In addition there will be a gravitational load that depends on the mirror mass. Each of these presents a different character. The overall weight per unit area of a mirror is around 2800 Pa for the light borosilicate honeycomb. 500 Pa acts on the facesheet alone. It is completely predictable and changes its orientation with respect to the mirror only slowly. During polishing, loads of typically 500-2000 Pa are used for pitch laps. This load is taken directly on the face, and causes local distortion of the facesheet comparable to or a few times that of gravity. However, the final stages of polishing are generally undertaken with small laps, so global bending is not an issue. Wind load depends on the telescope site and effectiveness of the enclosure. As a working upper limit we take the pressure felt face-on into a 10 m/s wind, that is about 50 Pa. Although relatively small, wind force is unpredictable, does not exert a uniform pressure, and can change rapidly.

A honeycomb sandwich mirror is characterized by three dimensions in addition to its diameter. These are its overall thickness, facesheet thickness and cell size. In a well optimized structure the two faces are about the same thickness, and the rib thickness is chosen so the ribs contain about half the total mass, so we will not treat these as further independent parameters. The faceplate thickness was already chosen on thermal grounds to be 25 mm. Cell size and overall thickness remain to be determined to give the necessary stiffness.

Cell size is driven by the requirement that the unsupported facesheet above each cell does not deflect appreciably under gravitational or polishing load. The surface depression appears as a bump after the polishing tool has passed over. Larger cells could be tolerated if stiffening ribs were cast below the face, however these would interfere with the ventilation flow, so we prefer simple hexagonal cells. The plate above each then deflects rather like a circular plate clamped at the edges and under uniform pressure. In this case the deflection δ at the center is given by

$$\delta = \frac{3}{16} \frac{qa^4(1-\nu^2)}{Et^3}, \qquad (1)$$

where q the applied pressure, a is the cell diameter, t the faceplate thickness, E the Young's modulus of the glass and ν its Poisson's ratio, (Roark, 1982). Values for E6 borosilicate are given in table 2 below. For thickness t=25 mm and pressure 1000 Pa (.144 psi) we find deflections of 6.3, 20 and 49 nm for cell diameters of 150, 200 and 250 mm respectively. For convenience of manufacture and ventilation it is desirable to make the cells as large as possible, consistent with acceptable deflection.

The effect of diffraction by quilting of rms amplitude σ by cells with separation s is to scatter light into a halo with angular radius r and containing a fraction f of the energy given approximately by

$$r = \lambda/s \tag{2}$$

and

$$f = (4\pi\sigma/\lambda)^2 \tag{3}$$

(Ruze, 1966). With 200 mm cell size, the halo diameter is larger than the seeing core, even at ultraviolet wavelengths where the scattering is strongest. We set as a criterion that the scattered fraction at 350 mm wavelength should be less than 20%. It follows from equation 3 that σ should be less than 12 nm, and hence the peak-to-valley quilting should be no more than about 40 nm.

For the detailed 8 m design studies we have chosen 193 mm cell spacing, that is 223 mm diagonally across the hexagon. The predicted peak-to-valley quilting is thus about 20 nm at modest polishing pressure (1000 Pa). The validity of this choice has been checked by polishing a number of mirrors with cells this size, some of which are now in use in telescopes. The most extensively tested was polished at rather high pressure, about 1600 Pa, and shows 30 nm bumps related to the honeycomb structure, (Roddier and Roddier, 1987). Very recent results obtained at the Optical Sciences Center with pressure of 500 Pa show much lower levels. On the basis of the present experience we are confident that quilting can be kept at negligible levels with the 193 mm cell spacing.

There remains the choice of overall thickness, which is chosen primarily to give adequate stiffness against wind. This depends on the type of axial support used. For the type in which distributed force actuators are used to exactly balance the weight, for example, counterweights, then the wind force is unbalanced and bends the mirror against the three points that define its orientation. It is better to use a whiffle tree type that automatically spreads wind as well as gravitational load over many points. Other types of support that act effectively like whiffle trees are interconnected hydraulic pads, or air pads that are servoed in three groups to null the force on the defining points. There is a residual error even with these supports, because the wind is not felt uniformly by the mirror surface. The three reaction forces will adjust to balance total force and moment, but cannot balance in detail. The mirror must be stiff enough to hold its shape against the residual moments.

The effect of the combined pressure of non-uniform wind and whiffle tree reaction can be estimated from existing data (Woolf, 1988). The deflection by an 8 m honeycomb of 630 mm average thickness under a 61.3 Pa load, and supported by three hard points, is given by Ballio et al (1988). The result is 410 nm rms, and consideration of the structure function shows distortion of about three times the target level for 0.06 arc second images. In this case the bending moments in the mirror are of order 100 N-m, are taken over scales of around 2 m, and are causing higher order aberration, not simple curvature changes. Now consider as an example the case of a wind pressure that varies from zero to 60 Pa across the mirror and is balanced by reaction from a whiffle tree. The three discrete reaction pressures will leave local resultant pressure imbalances of typically 10 - 15 Pa. In this case the moments in the glass will be about the same scale length as before, but about 4 times smaller. Thus we are confident that at 630 mm thickness the honeycomb will not be subject to any significant wind induced bending at the 0.06 arc second level.

On the basis of the above considerations of stiffness, we have adopted the following baseline design for the mirrors for the Columbus and Magellan telescopes:

Table 1

Baseline Design for f/1.2

shape:	plano-concave
focal ratio:	f/1.2
diameter:	8 m
facesheet thickness:	25 mm
rib thickness:	12 mm
outer edge thickness:	.84 m
inner edge thickness:	.43 m
cell shape:	hexagonal
cell spacing:	193 mm
mass:	14000 Kg

Distributed axial and lateral supports to balance this design against gravity have been analyzed by Ballio et al. (1988). The mirror is stiff enough that random errors of up to 1% can be tolerated in the axial supports. If the mirror is horizon pointing and all the weight is taken by vertical forces at the outer edges alone, an rms error of 59 nm is calculated. This falls outside the 0.06 arc second limit, but can be corrected by applying an appropriate distribution of axial forces, or by taking part of the axial load on lateral supports that reach into the honeycomb cells from the back. A thicker (1 m at the edge) and slower (f/1.8) design with similar cell size has also been analyzed by Pearson, Stepp and Keppel, (1988). Performance at the 0.06 arc second level was obtained. In this case lateral supports were distributed across the back face, but again residual aberrations needed to be compensated by moments from the axial actuators. Very recently Ballio et al. have discovered that edge forces alone, applied at appropriate angles to the face plates, provide lateral support that may have no need for further correction.

The accuracy of finite element analysis for prediction of thermal and mechanical deformation of honeycomb structures has been verified by direct comparison with a 1.8 m mirror (Pearson et al, 1986). We, therefore, feel secure that the 8 m design of table 2 will in reality give the desired performance in a basically passive mode. The tolerance on support force accuracy (1%) and temperature stabilization (0.1°C) are not unduly severe.

It is interesting to compare the performance of the baseline honeycomb design with that of uniform solid discs. Analytical expressions are given for bending deflections under various support configuration by Nelson, Lubliner and Mast (1982). Neglecting the effects of shear and shell stiffness, a disc supported by three points at the optimum radius for minimum deflection, (r/a = 0.645), has an rms surface error given by

$$\delta_{rms} = .0758 \frac{qa^4(1-\nu^2)}{Et^3} \tag{4}$$

where the rotation is the same as for equation 1, and the glass parameters are as follows:

Glass Type	Density (Kg/m^3)	Young's modulus (N/m^2)	ν
borosilicate (E6)	2180	5.75×10^{10}	0.195
glass ceramic (Zerodur)	2530	9.1×10^{10}	0.24

Table 2

As mentioned above, Ballio et al. (1988) find that on a three point support and under a 61.3 Pa uniform load, the 14 ton baseline honeycomb design has a 410 nm deflection. If the same weight of borosilicate glass were in the form of a solid 8 m disc 128 mm thick, we find from equation 4 that the deflection under similar conditions would be 9.29µm, more than 20 times larger. A solid disc of Zerodur of the same 14 ton weight would be 110 mm thick and show an almost identical rms deflection of 9.23µm. An increase of thickness to 311 mm, and the weight to 40 tons, would be needed to get the same 410 nm rms deflection against the 61.3 Pa external load. A 25 ton solid disc of 200 mm intermediate thickness would be nearly 4 times more flexible against external load, and nearly 7 times more against its own weight. A scheme of frequent image monitoring to determine figure and support force corrections is advocated for such mirrors (Enard, 1988). Furthermore, even at this thickness the mirror is still unable to achieve thermal balance with the night air, having a time constant of 7-14 hours, depending on how much wind exposure is provided. This should be compared with values of typically less than 1 hour for borosilicate honeycomb mirrors. In summary, for 8 m mirrors the honeycomb design offers very significant advantages in all three critical areas of weight, stiffness and thermal response.

3. MOLD DESIGN AND CONSTRUCTION

We have developed a technique to cast borosilicate honeycomb in one piece. The principle of the method is shown in Fig. 1. Hexagonal refractory cores are anchored to the floor of the cylindrical mold. Glass chunks set in the mold are melted and the liquid glass runs between and under the cores to form the backplate and ribs. The furnace is rotated while the glass is liquid, so as to form a curved free surface above the cores. After the glass has been annealed and cooled, the cores, now captured in the glass, are broken up and removed through the holes in the backplate left by the anchoring bolts. The process has been tested and developed during the casting of a number of trial blanks of diameter 1.2 m (1) 1.8 m (3) (Goble et al. 1986) and, most recently, 3.5 m. The casting of this last blank is described in Section 5.

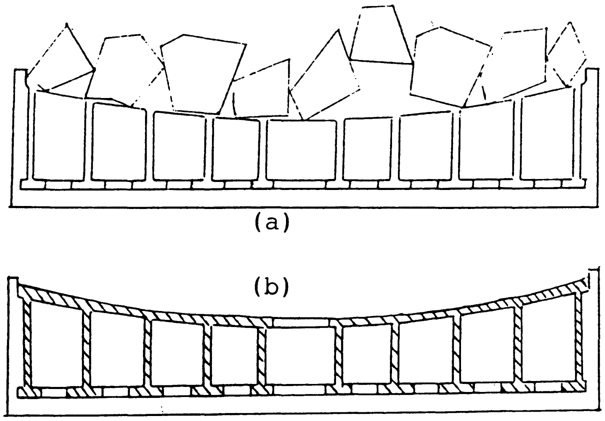

Figure 1. Schematic diagram of the honeycomb sandwich casting process. (a) shows the glass chunks before firing, and (b) after melting and spinning.

At the heart of the mirror fabrication process lies the mold. The success or failure of a casting depends on its integrity. Dimensional tolerances in the honeycomb structure can only be as good as those held in the machining and assembly of the mold. It must resist the large forces and thermal stresses acting during the casting process. The cores in an 8 m casting will feel a total buoyancy force of some 50 tons, as well as centrifugal force. Thermal stresses can arise because of large differential expansion effects, amounting to 20 - 30 mm across an 8 m mold, and must be uniformly distributed to avoid significant cracks developing, through which glass could escape.

The molds for all three 1.8 m and the 3.5 m trial castings have been built on the following principles (Hill and Angel, 1983). The buoyancy force on each hexagonal core is taken locally through a bolt connecting it to a matching hexagonal floor tile. The up-thrust on the core, limited to about 400 N for the deepest cores in an 8 m mold, is always exceeded by the downward hydrostatic pressure on the tile. The full array of floor tiles is locked in place in compression by a ring of curved vertical tiles that form the cylindrical side walls of the mold. These tiles are in turn compressed like the staves of a barrel, by metal bands. Tension in these bands is maintained as they expand by passing their ends out through the furnace walls, where they are attached to cold springs. These have to be outside because there are no practical springy materials at 1200°C. Made in this way, the molds have proven reliable and hold their overall dimensions to better than 1 mm, despite repeated thermal cycling and the weight of the heaviest core-installer crawling over them.

While the primary load is the upward buoyancy, other smaller forces must be allowed for in the mold. A substantial centrifugal force acting radially inward on the cores is produced by the rotation. In addition, there may be considerable imbalance in the hydrostatic force if the glass starts to flow down one side of a core more than another. The mold is therefore stabilized laterally by cross-pins that link all neighboring core faces. In the 3.5 m mold these are not taken to the outer perimeter wall. Anchoring here would result in a build up of radial tension, and there is no easy way to make an edge connection very secure. We have optimized the design using finite element analysis of the mold to minimize stresses consistent with measured material properties. Details of the mold construction are shown in Fig. 2.

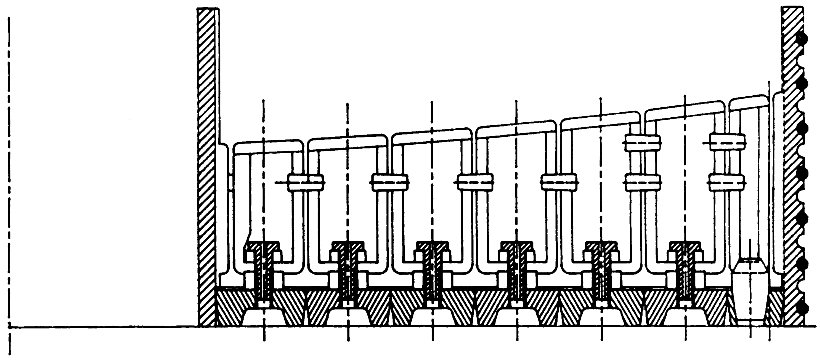

Figure 2. Radial cross section of the mold for the 3.5 m casting. Hard refractory pieces are hatched, and the inconel bands are shown solid.

A key to the mold's success has been finding materials that work well at 1200°C. Three types with different properties are used: hard refractory cement to cast into the tiles, nickel alloy for the tension bands, and ceramic fiber for the hexagonal cores and all surfaces that contact the glass.

The ideal hard refractory cement must be cast into the hundreds of intricate and threaded mold pieces, be strong and stable at 1200°C and conduct heat well. We used high alumina content material for the 1.8 m castings, but as a result of extensive testing have switched to a silicon carbide based material. This has better thermal conductivity, negligible electrical conduction and strength equal to that of the alumina. The castings are all pre-fired to 1200°C before use, to establish their final strength and dimension. (There is 0.5% linear shrinkage). Final fitting of the hundreds of hexagonal tiles and wall sections is made by sand and water blasting. The first 3.5 m casting uses twenty-four cylindrical curved sections form the inner and outer walls. The base has 294 hexagonal and part-hexagonal pieces, each with cast feet and a threaded central hole to take a core-anchoring bolt.

The bolts are also made of silicon carbide, but in this case a purer, stronger form. They are machined from an extruded pre-form containing carbon and silicon carbide particles, and then commercially fired in liquid silicon. It is the same process used to make silicon carbide heater elements.

Compression of the 3.5 m mold is by 24 2.5 cm diameter curved rods, tensioned by external springs to 1000 N each. The alloy used, Inconel 601, has one of the highest strengths of any base metal alloy that resists oxidation at 1200°C. Loaded at 2 MPa, it yields less than 10^{-3} per firing and so will be good for many castings. The material also sheds a fine oxide powder at 800°C as it cools, but is stable against oxidation at 1200°C.

The most critical material in the mold is that used to line the base and walls, and for the hexagonal void-leaving cores. It must be strong enough not to deform under hydrostatic loads, yet be weak enough to avoid cracking the glass and to be removable from the cooled blank. It must not interact chemically with the liquid glass but it must be sufficiently porous to allow air to escape from the bottom of the mold as glass runs in from the top. An ideal material we have discovered is the insulating board made from refractory aluminosilicate glass fibers, and commonly used in many furnaces. The Rex-Roto company has the most promising material and was willing to work with us to improve it. They have supplied all the boxes for the recent 1.2 and 3.5 m castings. A test casting at 600 mm depth shows only the slightest compression from the hydrostatic load.

The fiber is vacuum-formed at the factory over hexagonal tools, and is supplied to us with a bark-like surface. These preforms are fired to 1200°C, when they shrink about 3% in linear dimension. Then each part is machined to a tolerance of about 100μm. In the past shaping was done less accurately using woodworking tools using carbide toothed blades. We now use a special machine developed by Larry Goble, which incorporates two saws, an index head, a grinding table and a drill press. It has fixtures that pick up the internal cavity of a hexagonal core, and allows all the cutting and boring operations to be made with only one rechucking for the final cut-off. In practice with this new machine the core manufacture proceeds very quickly. The fired material is very friable and cuts can be taken at 20 mm/sec. Vacuum chucking is used for rapid handling of the parts.

4. 8 m FURNACE AND STADIUM LABORATORY

The 1.8 m f/1 honeycomb blank was cast in an experimental spinning furnace of 2 m capacity. On the basis of this successful demonstration, the decision was taken to move directly to build a facility and turntable sized for spin casting 8 m mirrors. This is now largely completed, and we have avoided the expense of developing intermediate size casting facilities. However the first trial at 3.5 m has come later than would have been possible if we had settled for the intermediate goal.

The new facility has been built under the grandstands of the University of Arizona football stadium. Construction was started in November 1984 and completed in July 1985. A 40 ton crane was installed in November 1985. The first part of the furnace to be completed in the new building was the 12 m diameter turntable, in March 1986. It is supported by a single, 3 m diameter crossed roller bearing. A ring spur gear is machined into the stationary race of the bearing. Drive torque is applied by two separate pinions, countershafts, gearboxes, drive belts, motors and power supplies, providing a double redundancy in the drive system. The speed is stable to 0.1%, the design specification. A stack of 8, 1/4 MW slip rings specially designed for the furnace was installed in the central support pedestal in November 1986.

Furnace and Control System

The full size furnace to be used for 6.5 meter and 8 meter castings will have an internal diameter of 9 meters. There will be a cylindrical wall 1.2 m high, topped by a flat disc and conical lid section (Figure 3b). For tests at 3.5 or 4 m diameter we have built a subset of parts, and from those have assembled a furnace with 6 meter internal diameter, 1.2 meters high. (Figure 3a)

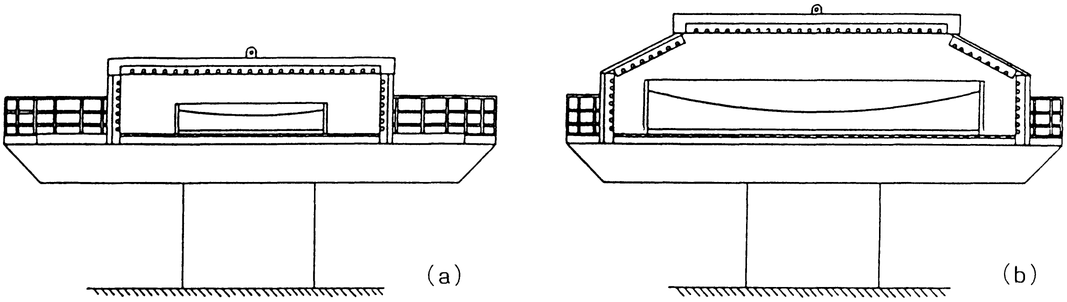

Figure 3. (a) shows the present 6 m furnace configuration, with a 3.5 m mold. (b) shows the same flat lid and wall sections rebuilt for 8 m casting.

The furnace has as major components a hearth, walls and lid. The circular bottom plate, or hearth, is pieced together from smaller, pie-shaped segments of hard silicon carbide based refractory. Each segment contains grooves for heater element coils. Insulating refractory bricks support the hearth at the corners of each individual hearth plate. The space between the turntable surface and hearth bottom is filled by an insulating blanket. The brick ends are rounded so that the hearth can expand or contract freely while remaining flat and level. Segments originally fabricated by the Carborundum Company became slightly electrically conducting at full casting temperature, and have been largely replaced by new segments made in house. The lid and sidewalls, also made in-house, form the outside shell of the furnace. The "hot side" of the walls and lid are faced with commercial panels containing wound Kanthal Al wire heater elements and backed by a layer of blanket insulation.

The design for the full 9 m furnace incorporates 270 individual radiant electrical heating elements of 7.7 KW each. In the 6 m intermediate sized furnace, 108 of the elements are being used. 60% of the heaters are connected to the grid and the rest to a 250 KVA generator. In operation, holding at 1170°C the furnace is measured to need 130 KW of power. In the event of a line failure the generator will have enough power to heat up the casting, at a slower rate.

Each 25 amp, 277 volt heater is switched under computer control by a solid state relay. These in turn are each protected by a fast acting fuse and circuit breaker. The reliability of this configuration has been proved in practice. Arcing inside the furnace does not result in a short circuit, but first trips the breaker.

Temperatures in the present 6 m furnace are sensed by 180 N-type thermocouples. These are read several times a minute, and a scheme of temporal and spatial inter-comparison eliminates erratic or inconsistent measures. A servo algorithm then determines the distribution of power to the heaters, arranged in a number of independently controlled zones. We have made serious efforts to achieve high reliability in the control system because incorrect heating during the long annealing (one month and longer) could crack a blank. High reliability CMOS microcomputers are used on board the furnace, and are battery-backup powered. Data links are via fiber optics. Fine tuning of the servo algorithm has resulted in control of the entire furnace to 1^{o}C has been realized at the annealing temperature of 500^{o}C. The mean power loss of the furnace at this temperature is only 30 KW.

5. 3.5 m TRIAL CASTING

The past year has been a series of major steps in the honeycomb casting development program, culminating in the casting of the first trial at 3.5 m diameter. The 6.5 m furnace configuration underwent preliminary heating and spinning tests in the summer of 1987. Its first operational test came with the trial spin casting of a 1.2 m blank in November. Most of the many new systems performed very well. We did, though, have a significant failure of the control computer during annealing. No permanent damage was done, and the blank is now being polished for a telescope. We did though restart the anneal sequence of cooling to be absolutely sure that the cooling during less of power would not leave any permanent strain in the glass. Subsequently, we have taken a number of additional steps to improve the hardware reliability, and the high level software that monitors and displays the control status and record. For the 3.5 m casting the on-board control computer was connected via slip rings to a SUN work station in the control room. This monitors all aspects, and includes IRAF displays of temperature contours.

Starting with an empty furnace in mid-December, it took just four months to fabricate and complete assembly of the first 3.5 m mold. The process starts with the assembly in the furnace of the hexagonal base tiles, already faced with ceramic fiber board. The base and wall tile were installed with the nichrome bands, and then the furnace fired to 1200°C to settle the bands in the tile grooves. From this point on the band tension was never relaxed, and the tiles remained locked rigidly together by friction. After cooling, the curved walls were lined with fiber board and a 15 m long bridge set across the turntable, so it could be used as a vertical lathe. A cylindrical wall and flat base surface were then machined into the fiber lining.

In the meantime the 294 hollow hexagonal cores had been machined. Tilted cuts were made at the top, to follow the f/1.75 curve of the mirror, but the tops were left open so the anchoring bolts could be inserted. Accurate location of all the cores in the mold was achieved by dry fitting them with spacing rods of Y cross section at every corner. Each core was then bolted and glued to its base tile. Holes for the 1000 cross connecting pins were drilled in situ, and the pins installed with glue. Finally the hexagonal core tops were glued on to complete the mold. Engraved across the face of the mold is the name Marc A. Aaronson.

The casting process was started on April 11 with a firing to 1170°C of the empty mold, to set the glue joints. A final inspection followed showing that the mold geometry was very accurately preserved despite the expansion and contraction of mold during firing. Loading with 2200 Kg of E6 glass took only a few hours, and then heating started on April 23. Softening and settling of the glass was observed with the TV monitors to start as the temperature reached 700°C, when the rotation was started. This was held constant at 8.54 rpm. As heating continued, the glass first melted together to form a clear surface with the mold visible underneath. Only as the temperature passed 1100°C did the viscosity become low enough for the glass to run down the 10 mm wide gaps to form the ribs. In this casting the glass surface remained undisturbed as the level then dropped 70 mm to fill the mold and form the honeycomb structure.

The temperature was held at the 1170°C peak value for several hours, and then cooled to start the slow annealing at 520°C. At around 700°C while the furnace was still spinning the lid was raised by .5 m for two minutes, to allow visual inspection. The curved face was clear of good thickness and with no detectable bubbles (fig. 4) and the regular pattern of cores observed to be undisturbed by the casting stresses. Thus the trial has already given a successful test of the stability of the mold. At the time of writing the annealing process is complete, and the blank is slowly cooling to room

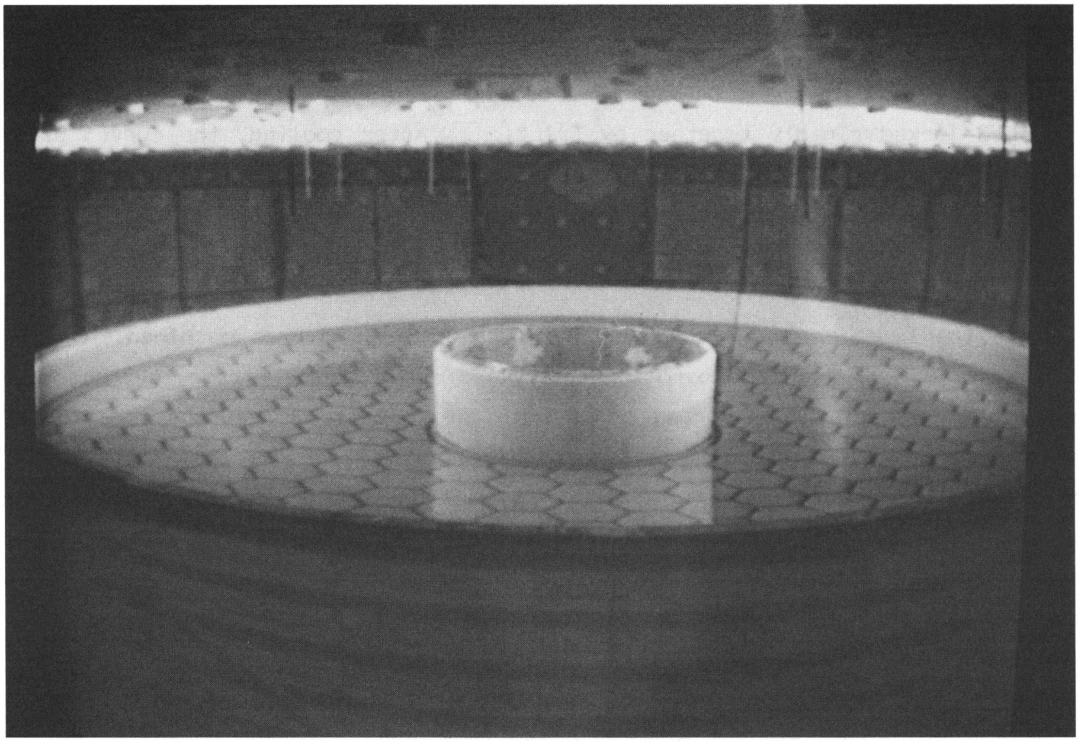

Figure 4. View from the TV monitor of the 3.5 m honeycomb casting.

temperature. The complete furnace cycle will take six weeks.

While everything so far points to a successful first trial, the quality of the blank will not be known until it has been removed and cleaned out. When the furnace is opened, the wall tiles will be removed and the blank, with base tiles still attached, lifted from the face by a whiffle tree arrangement with 18 pads 0.5 m in diameter. It is crucial at this stage to avoid stress in a casting, which typically will have some small surface cracks associated with glue joints in the mold. Normal strength is not achieved until the tiles are removed and these are ground off.

6. CONCLUSION AND ACKNOWLEDGEMENTS

The impetus for borosilicate honeycomb mirrors originated with the proposal to build a U.S. national telescope with four 8 m primaries, (Angel and Woolf, 1986), a plan now sadly in limbo. Nevertheless, the opportunity to make advanced and affordable research facilities with the developmental intermediate sized mirrors as well as the 8 m mirrors has been seized by the U.S. community. The first successful 3.5 m blank will be used by the ARC consortium for the Apache

Point observatory. The second will be used by the Universities of Wisconsin, and Indiana together with and NOAO, while the 6.5 m trial will be used to replace the six 1.8 m mirrors in the MMT. Then 8 m borosilicate honeycomb mirrors will be used by the Columbus and Magellan projects. The NOAO is preparing proposals for 8 m telescopes that will recommend borosilicate honeycomb as a first choice.

The cornerstone on which these projects are being built is the honeycomb mirror technology development program. We would like to acknowledge the crucial role of the NSF in supporting this program, currently through a subcontract from the National Optical Astronomy Observatories. The University of Arizona has also supported the program by providing the Mirror Laboratory and an 8 m optical generator, the world's largest. A $1.8M extension to the Mirror Lab to house the generator and a new 8 m polishing machine is to be constructed by the University in 1989.

Monumental efforts to bring the casting technology to its present state have been made by many individuals. I particularly want to acknowledge the leader ship of Larry Goble, John Hill, Dana Mitchell, Buddy Powell and Peter Strittmatter at Steward Observatory. Ed Mannery, of the University of Washington, Larry Daggert and Larry Stepp of NOAO, have been very helpful to the project.

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DISCUSSION

P. BELY: Why do you keep the back surface of your mirrors flat? With fast f/ratio weight savings afforded by a convex back surface should be significant.

J.R.P. ANGEL: Finite element analysis (see papers by Stepp and Ballio) shows that the stiffness and support is not compromised by the variable thickness. Manufacturing is easier with the flat back, and so is the placement of axial support pads.