PROGRESS REPORT — THE 200-INCH MIRROR

By PROF. J. A. ANDERSON

This article reviews briefly the history of the 200-inch mirror to date, and relates in some detail the problem of gravitational astigmatism. Sveral additional interesting problems are set forth.

The 200-inch mirror disk was cast at the Corning Glass Works in March, 1935, and arrived at Pasadena in April, 1936. The structure of the disk is indicated by the oblique photograph reproduced in Figure 1, showing the back and rim, and the diagram, Figure 2, showing a section along the line *AA* of Figure 1. In general it may be described as a continuous glass front supported by a system of glass ribs, so designed that when a concave curve is cut in the front surface (shown by the dashed line in Figure 2), the thickness of the glass shall be nearly the same everywhere. This construction was chosen in order to reduce the 'temperature inertia'* of the disk as a whole to a low value. It also makes it possible to bring the point of support of each supporting lever closer to the center of gravity of the weight to be supported. For this purpose there are 36 circular openings in the rib system to accommodate the same number of supporting levers. Figure 3 shows one of the supporting units which is 'double-acting'; that is, it takes the place of both the ordinary back and edge supports.

The work of shaping this disk into a finished mirror is not essentially different from that required for a smaller mirror familiar to all amateur telescope makers. Front and back must be ground flat and parallel to each other, and the edge ground to the form of a reasonably good circular cylinder. In addition, the 200-inch required that the 36 circular openings for the supporting levers be ground internally to very definite dimensions. An important difference arises from the great size and weight of the 200-inch; namely, that machinery is called for at every turn—and rather heavy and slow moving machinery at that.

For the rough shaping a half-sized tool of cast iron was prepared. Its weight was about seven tons. It was made thick enough to be used first as a flat grinder and later on to be turned convex for roughing out the concave curve of the mirror. All other tools, including one of full size, were built up of thin sheet-steel plates welded together. These are much lighter than cast tools of the same size and they have also been found to be superior in rigidity. The working surfaces of these tools are covered with glass blocks which are used uncovered for grinding and covered with pitch substitute for polishing. The weight of the full-sized tool (shown on the floor to the left in Figure 4) is about five tons.

In order to grind the back surface to a tolerably good plane, it was necessary to fill up the openings between the ribs. Little wooden tables were made and fitted into these openings in such a way that the tops of the tables lacked about 2″ of being flush with the ribs. Plaster of Paris was then used to complete the filling. Only in this way was it possible to grind the surface to a true plane. This done, the cavities were cleaned of plaster and tables and the disk turned over in preparation for the next step, which was to grind the face plane and parallel to the back.

Normally, this should have required a relatively short time, but actually it took many months, chiefly for the following reason: Corning had a considerable flood in 1935 while this disk was in the annealing oven. Water covered the floor of the room where the annealing was in progress to such a depth that it was necessary to shut off the current for about three days. A temperature drop of rather large amount was the result, but as soon as conditions permitted the temperature was slowly brought up to its normal value and held there constant for a time. Then the regular program of slow cooling was resumed. When, in late October, 1935, the disk was examined, it was found quite successfully annealed, but there were some bad-looking fractures in the front surface. The immediate cause of these fractures was clear, for a couple of the chrome-iron I-beams of the cover had sagged enough to become partly imbedded in the hot glass and, as the cooling proceeded, strains due to the differential expansion of iron and glass did the trick. One has a feeling that this would not have happened if there had been no interruption in the cooling, but, of course, this can now never be known with full certainty.

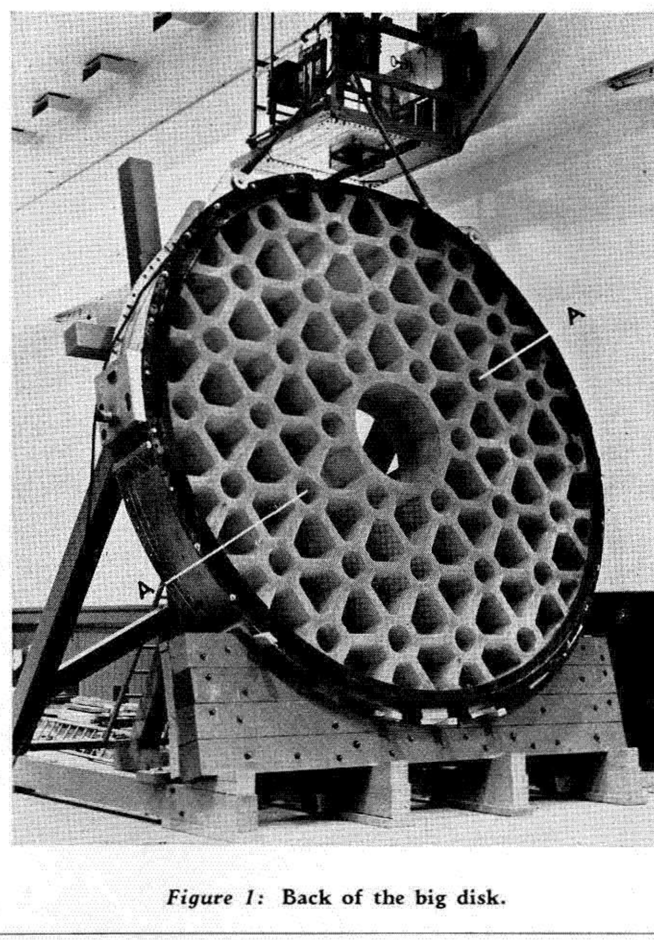

Figure 1: **Back of the big disk.**

1 "Temperature inertia" is a convenient term to indicate the length of time required for the temperature to reach equilibrium with the surroundings.

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The obvious thing to do was done; namely, to remove the fractures by sand blast and so find out whether sufficient thickness of glass remained to make a good mirror. The deepest excavation made in the sandblasting was over 5″ deep but it was near the center of the disk, so it would still be possible to grind the concave curve and have a glass thickness of 4″ left. If the disk had come out as planned, this thickness could readily have been 6″ or a little more, which might have been an advantage if rigidity alone is considered. A thickness of 4″ is, however, slightly better from the point of view of low temperature inertia, since all the ribs have about this thickness.

It was decided that, instead of merely making the front surface into a true plane, the extra 2″ of glass should be ground off before establishing the plane and making the disk parallel. This 2″ of glass represented a weight of 2½ tons and used up five tons of coarse Carborundum. Later on, another 2½ tons of glass would have to be removed in cutting the concave curve.

Grinding the edge was the next operation. This was done face down, with the face of the mirror raised some 8″ above the turntable by inserting suitable timbers. The grinding was done with a rotating hollow cylinder of Carborundum fed with water and Carborundum powder. The 40″ central hole was ground to size in this same set-up.

The next step was grinding the 36 cylindrical holes designed to admit the supporting levers. The axes of these cylinders should be perpendicular to the parallel planes of the front and back already established, and, in addition, their spacing should be adjusted to form a regular geometrical pattern. A special 'pocket-grinder' had been prepared, carrying at its lower end a cast-iron hollow cylinder about 11″ outside diameter. The rotating shaft carrying this cylinder could be given a slow motion in a circle having a radius variable slowly and accurately from nothing up to whatever the size required for the finished 'pocket'.

The 36 pockets lie on five concentric circles, six on each circle except the fourth one (counting out from the center), which has 12. On circles 1, 2, 3, and 5 they are 60 degrees apart, while on the fourth circle they are spaced in six pairs 60 degrees apart, the members of a pair being separated by an angle a little less than 22 degrees. The whole operation of grinding these pockets was completed in about three months.

Next the turntable of the grinding machine was covered with two layers of 1″ sponge rubber and the mirror placed face-up on this bedding. In order to insure as uniform a support as possible the compression of each sheet of sponge rubber was carefully measured under a fixed load, and only those pieces whose compression was within a narrow range of being the same were applied to the table.

The glass plug to fill up the 40″ hole in the center of the mirror had been ground cylindrical to a suitable diameter, and it had to be inserted and fixed in place in such a way that, when the mirror is finished, it can be easily removed without any danger of harming the figure of the mirror. As the plug weighs about 1400 pounds, this did not look too easy. It was accomplished as follows: A wooden lifting clamp was applied to the upper half of the plug, leaving the lower ribbed section of about 15″ projecting below the clamp. A cake of ice about a foot thick was placed on the table in the center of the hole. By means of the crane it was then possible to rest the plug on the cake of ice. The clamp was removed and the ice melted, thus lowering the plug gently into its proper position, after which it was fixed in place by means of plaster of Paris and water-proof cement.

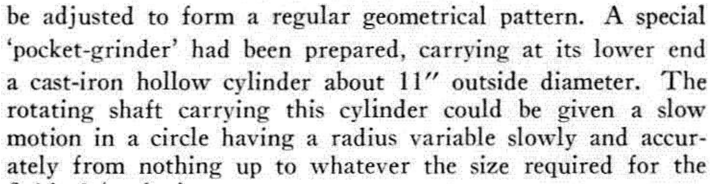
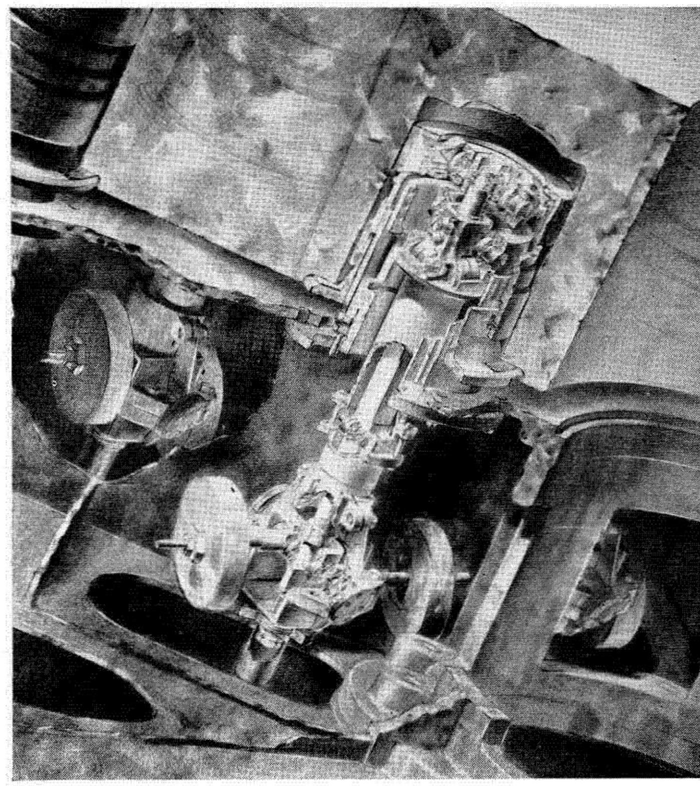


***Figure 2:* Sections along line *AA* in Figure 1, *p,p* are openings for supporting units. In the casting ,thickness at *a,a* was 6″, at *b,b* 9¾″. In finished mirror (lower dashed line) thickness is approximately 4″. Over all thickness at edge is 24″. Finished weight, nearly 30,000 pounds.**



Drawing by R. W. Porter.

***Figure 3:* Lever mirror support.**

Before cutting the curve the support system was installed. This operation took approximately eight months. In preparation for it the weight to be carried by each of the 36 units had been calculated on the basis of careful measurements on the disk itself. Each support pocket was taken as the center of a hexagonal section of the disk. The hexagons around the centrol hole (Circle No. 1) and those adjoining the outer edge (Circle No. 5) are not complete, which fact complicated the calculations only slightly. The calculations furnished the weight to be carried by each unit and also located the center of gravity of each arbitrary section of the disk, thus giving the necessary data for each counterweight and for locating the internal points of application of the supporting force. Each support (Figure 3) was carefully adjusted and tested on a weight equal to that which it was intended to carry before it was attached to the mirror and its cell. Provision was made for temporarily disconnecting all the supports when work was in progress with large tools. They were, however, connected properly when an optical test was to be made.

The curve was roughed out with cast-iron tools of about one third size, and brought to approximately correct form by means of the half-sized tool already mentioned, after which

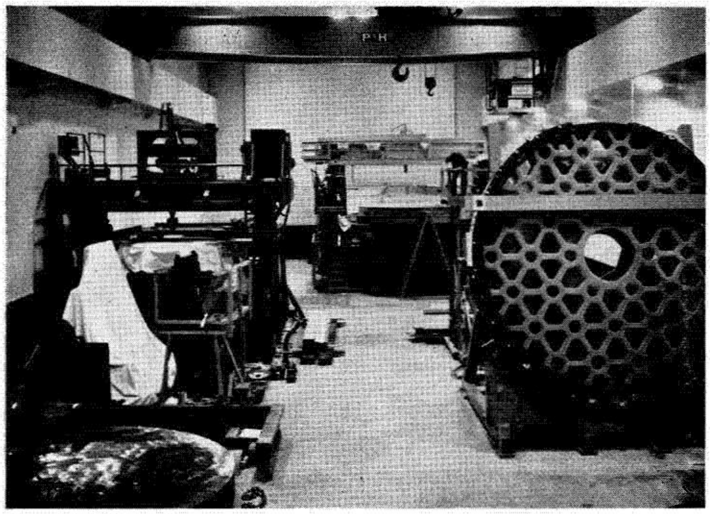


Fig. 4: **Five-ton full-sized steel tool.**

the glass-coated full-sized tool and the finer grades of Carborundum and emery finished the grinding. Measurements of curvature were made with a 36″ spherometer. Next, the full-sized tool was changed to a polishing tool, as already explained, and the surface brought to a nearly full polish. It was found that the full-sized tool used up rouge at the rate of some 50 pounds per hour, mostly by simply splashing it over the edge, hence subsequent polishing and figuring was done with smaller tools—106″ and down to about 12″.

Optical tests of the 200″ mirror were at first made with the mirror tipped up so its optic axis was horizontal, using therefore only the one component of the supporting levers. Later on, tests were made with the axis pointing about 4° above the horizon, so that both components of supporting force would be in action. In the later stages of figuring the mirror was made to rest on the supporting system while polishing was in progress.

The first optical test of the mirror, in September, 1938, revealed a fair spherical surface with some zonal and other errors, the chief of which was astigmatism. Measurement of the latter showed that the radius of curvature of a vertical plane was a millimeter or so shorter than that of a horizontal section. Rotation of the mirror about its axis in the testing position showed that the astigmatism did not rotate with it—in other words the radius of curvature in the vertical plane remained shorter in all positions of the mirror.

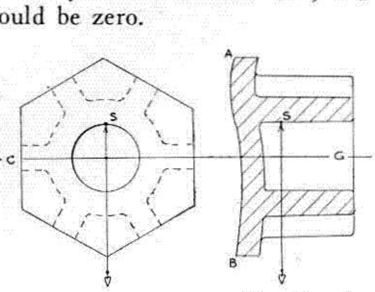
More refined measures revealed another surprising fact—namely, that at times the vertical astigmatism would have slightly different values in two orientations 180° apart. Running down the cause of this behavior required considerable time after it had been demonstrated to our satisfaction that the phenomena were real and not simply errors of measurement. A linear astigmatism of the order of 0.05″, with a not very smooth mirror surface where errors of measurement would average 0.01″ or 0.02″, does not seem so very bad—and the 180° effect of about 0.01″ might very well be considered accidental—as it was in fact until continued improvement in the figure reduced errors of setting to a few thousands of an inch. Anyway, both of these effects which had been noted in the early tests turned out to be real and correctable, though it must be confessed that it took a year or more to discover their nature and cause.

The cause of the vertical astigmatism lies in the structure of the mirror itself, combined, of course, with the method of internal support. Suppose the mirror is tipped up so that its axis is horizontal. Its weight then is carried by the 36 levers whose points of contact are in the rib structure and something like four or five inches behind the continuous front of the mirror. Let us think of one of the hexagons (Figure 5), into which we divided the mirror in the previous discussion, as made up of two parts: first, the solid front curved plate and second, the ribs. The front plate is about twice as stiff in a vertical plane as the rib system is.

If now the support point were located at the center of gravity (actually, on the axis of the 'pocket'), the half of our unit below the center of gravity would be in tension, so that it would stretch; while the part above would be in compression. Also, the deformation of the ribbed part would be twice as great as that of the solid front. If the undeformed front surface were a plane, it would, under this deformation, become slightly S-shaped vertically; that is, the upper-half would be slightly convex, the lower slightly concave. Since, instead of a plane, we have a spherical surface in the undeformed condition, the deformed condition will consist in the addition of a very weak convex cylinder to the upper half and a similar concave cylinder to the lower half of the unit. Taking now the whole mirror, each of the 36 parts would be similarly deformed, but there would be no general deformation of the surface as a whole.

Return now to the actual case. See Figure 5. The supporting point is on the upper surface of the 'pocket', which lies some 6″ or $6\frac{1}{2}$″ above the center of gravity. The part A that becomes convex is therefore 6″ shorter than the lower part near B, which becomes concave. So we may say that, on the whole, the unit is concave; and when we now add up the 36 parts we find, in addition to the local deformation of each unit, a general (net) vertical concavity of the whole surface, which is what has been observed. The diagrams of Figure 5 will perhaps aid in understanding this. The local deformations of each unit are of course present, but they are so very much smaller than the net deformation that, provided the latter is small, the former will be too small to be observed.

If, in Figure 5, the support S could be located on line CG, curve AB would be symmetrical about CG, and the net curvature of AB would be zero.



Drawing by R. W. Porter.

Figure 5: **Theoretical hexagon.**

Clearly the effect just discussed will be absent, or have zero value, when the axis of the mirror is vertical. As the mirror axis is tilted toward the horizon, the effect will vary as the sine of the zenith distance. To correct it, a system of 12 gravity-operated 'squeeze levers' were applied, acting on the outer edge of the disk near the back, which, when the axis of the mirror is horizontal, act so as to correct the error. Since their effect also varies as the sine of the zenith distance, the compensation will be correct in all positions of the axis.

The second phenomonen mentioned above—that is, vertical astigmatism in two orientations 180° apart—is caused by a maladjustment of the supporting levers, and, like the one just discussed, is absent when the mirror faces the zenith. Let us again consider the mirror tipped up, with axis horizontal, and assume that the supporting levers such as S, Figure 6, in the upper half are on the average so adjusted that their supporting points are somewhat in front of the center of gravity sur-

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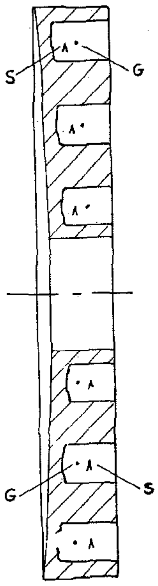
face in the mirror, while those of the lower half are misplaced in the opposite direction. Reference to the same figure will make it clear that, in the assumed position, the radius of curvature in the vertical plane will be lengthened, while if the mirror is rotated 180°, the radius will be shortened by the same amount. Here the remedy is obvious.

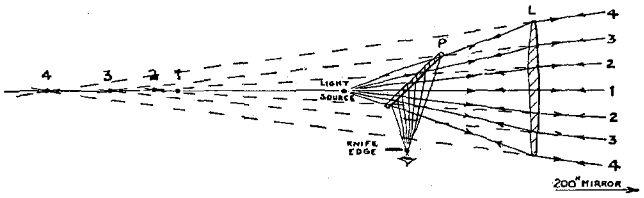


Drawing by R. W. Porter.

Fig. 6: **Cause of astigmatism.**

In order to test for astigmatism when the mirror faces the zenith, the arrangement shown in Figure 7 was employed. The light source and the knife-edge are, as usual, near *CC.* The plane mirrors *MM,* at 45°, are 8″ in diameter. By rotating the large mirror the zone indicated by the dashed line may be tested for astigmatism. By adjusting the counterweights of the 'lifting component' of the supporting levers, any observed small astigmatism may be removed.

The work of making the mirror surface a satisfactory sphere having a radius of curvature of 1335.7″ was completed in August, 1941. Parabolizing by alternate fine grinding and polishing was started August 30, and is now very nearly completed 'in the rough'; meaning thereby that the radii of zones



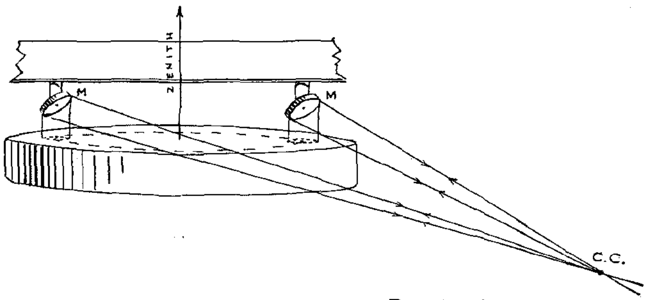
Drawing by R. W. Porter.

Fig. 7: **The method for testing by zones for astigmatism.**

are very close to the calculated values. The long work of smoothing and final figuring still remains to be done.

Testing will be done near the center of curvature, using a method worked out by Dr. F. E. Ross and the author. The method is new as far as we are aware; however, it would not surprise us if it should prove to be 'old as the hills'—for no complete search of the literature has so far been made. The method is shown in Figure 8. The lens *L* is so designed that, when the light source is placed at a point between its focus and the lens, the spherical aberration at its virtual conjugate focus is such that the conjugate focal points for different zones of the lens coincide with the 'centers of curvature' of the corresponding zones of the paraboloid. The light source is shown on the axis. *To the right of the lens the rays travel along* the normals to the paraboloid, whence they are returned along the normals and would converge to the source—but, by the aid of the half-silvered plate *P*, the returning light is brought to the knife-edge as shown. The source and knife-edge may be interchanged.

The author wishes to express his deep appreciation of the assistance given him by Russell W. Porter in the preparation of this article.



Drawing by R. W. Porter.

Fig. 8: **Testing method to be used in the final figuring.**