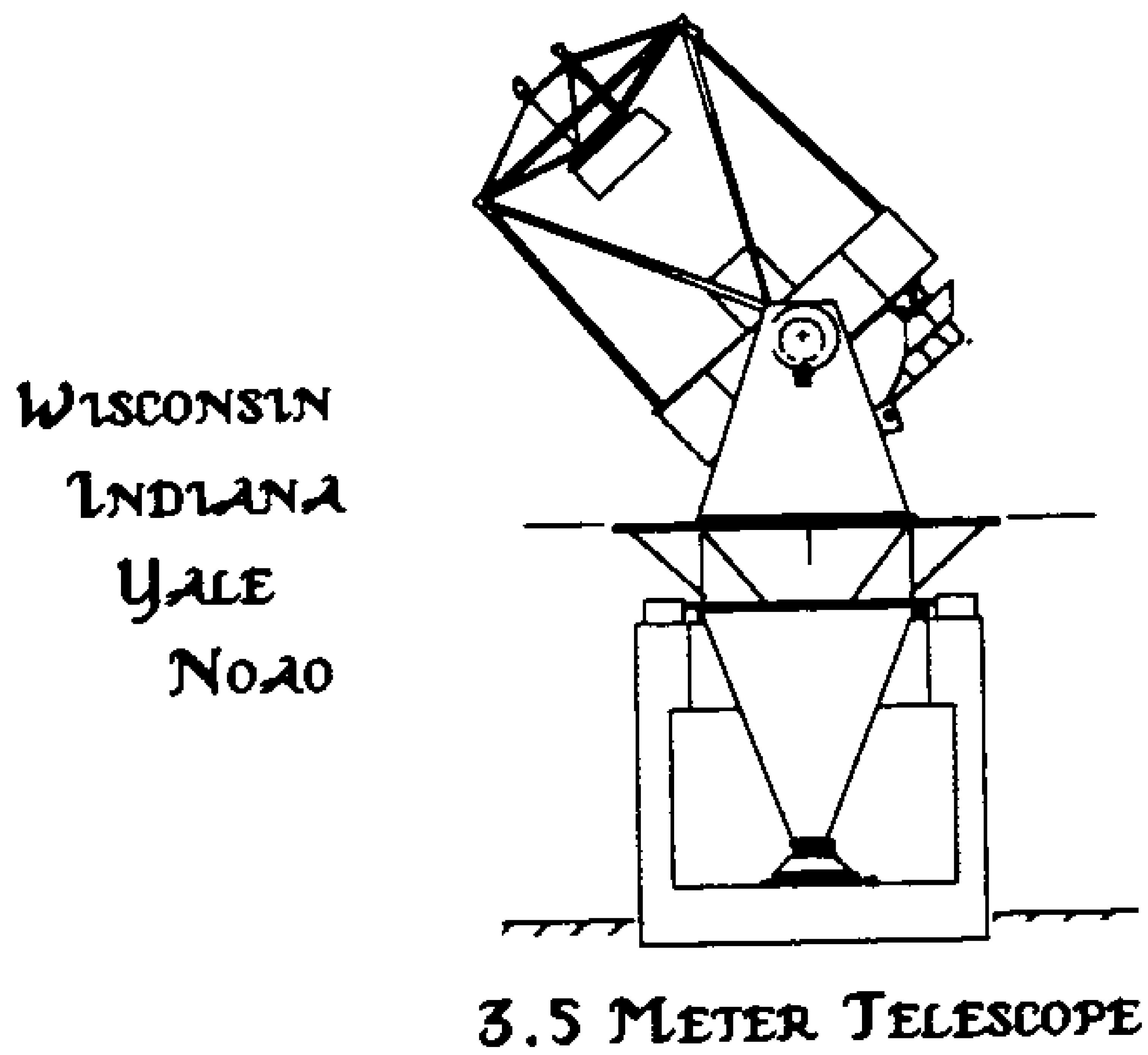


# Fabrication of the WIYN 3.5 Primary Mirror: Producing a Sphere

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Fabrication of the WIYN 3.5-m primary mirror: producing an accurate sphere

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## ABSTRACT

At the National Optical Astronomy Observatories (NOAO) we have been working to extend existing fabrication techniques necessary to polish and figure large, steeply curved, structured borosilicate glass mirrors to exceedingly close tolerances. This paper describes the generation, grinding, and polishing techniques used to transform a 3.5-m diameter, f/1.75, glass casting into a precision spherical surface. The accuracy of the finished sphere was 0.52λ peak-to-valley and 0.066λ (42 nm) rms.

## 1. INTRODUCTION

As a step toward the successful fabrication of 8-m diameter mirrors, NOAO has established a 3.5-m mirror project to develop and prove the necessary technical innovations. The 3.5-m borosilicate mirror blank was cast at the Steward Observatory Mirror Laboratory (SOML) from E6 glass purchased from the Ohara Corporation in Japan. The design of the mirror is lightweight, the front and back plates separated by a core of thin ribs in a honeycomb pattern. [1] Following the annealing cycle, the casting was taken from the oven and the mold materials forming the hexagonal shaped cores were removed. The mirror blank was placed into a shipping container and carefully transported by truck to our facility two blocks away.

## 2. RECEIPT OF THE 3.5-M BLANK

When the mirror blank arrived at the NOAO large optics polishing facility it was placed face down on an adjustable three-point support (see Figure 1). A structural model of the blank had been prepared and used to calculate the deformation caused by the three-point support and it was found to be an acceptable 8.9 micron peak-to-valley trefoil shape. The three screw jacks were fitted with angled top plates and were covered with 12-mm thick rubber pads that conformed to the curvature of the front faceplate. The position of the jacks on the polishing table was determined by the requirement they contact the faceplate at the intersection of three ribs. The rubber pads were given a liberal coating of silicone grease that allowed the casting to be centered about the rotational axis of the polishing table by adjusting four edge arcs. The edge arcs were contoured oak blocks, attached to 1-inch bolts, that pushed on the lower plate of the mirror.

The 4-m polishing machine (shown in Figure 2), was built in 1967 by L&F Industries. It is hydraulically driven, both in table rotation and stroking action, and features a tilt table to allow for horizontal testing of mirrors. In its original configuration, this machine was used to produce mirrors for several large telescopes, the first of which was the 4-m on Kitt Peak. Before we began this project we made two significant modifications to the machine. First, we mounted encoders on each of its axes of motion that allowed us to monitor the position of the machine during generating. Second, we built and installed a hydraulic tool rotation drive that was used extensively during grinding and polishing. Before the mirror blank arrived, the polishing machine was fitted with a large generator and the Pittman arm stroking motion was clamped. After the blank was placed on the polishing table the handling band and protective wooden covers were removed.

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††Operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

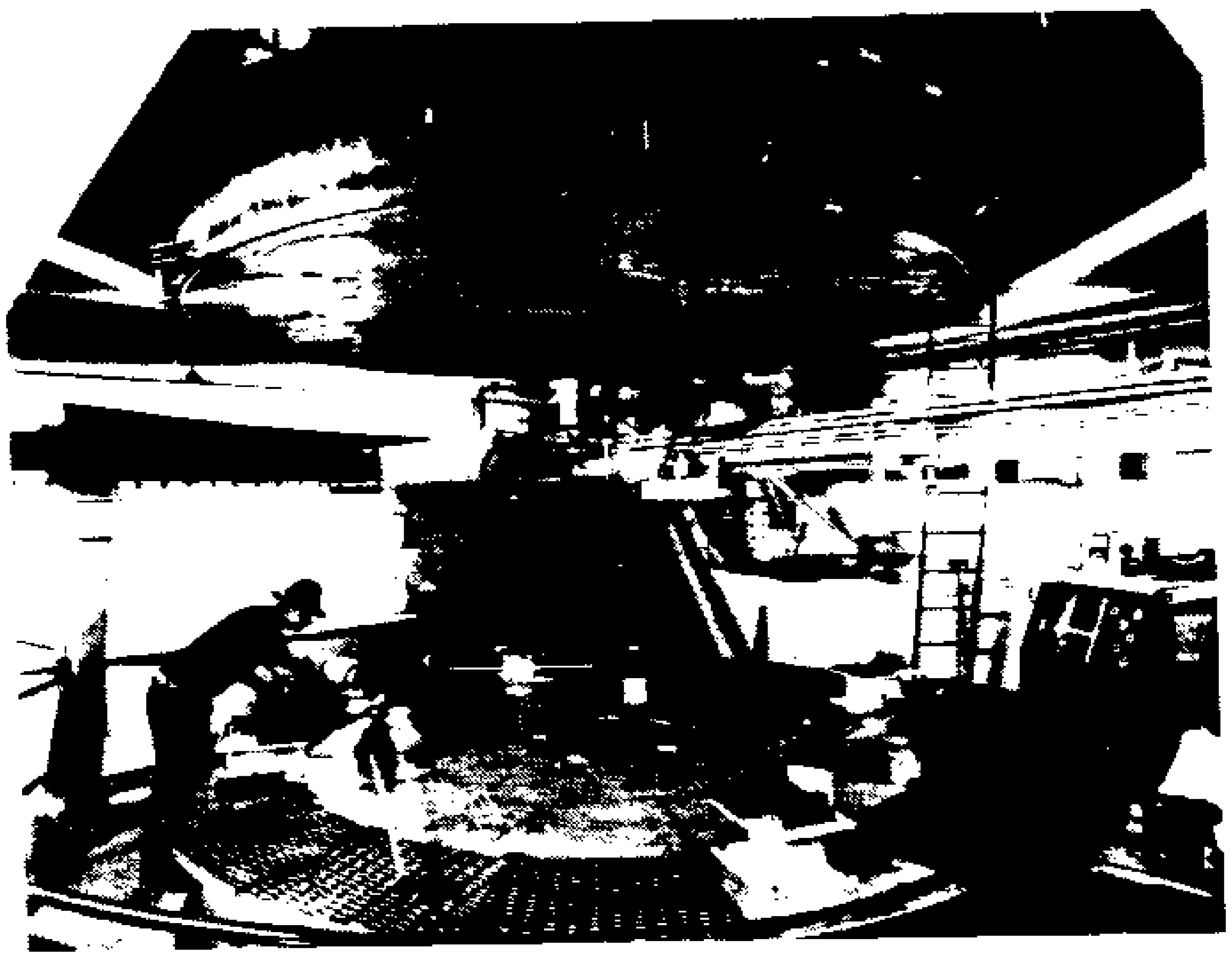

Figure 1. The 3.5-m mirror is placed face down on a three-point support for generating the back surface.

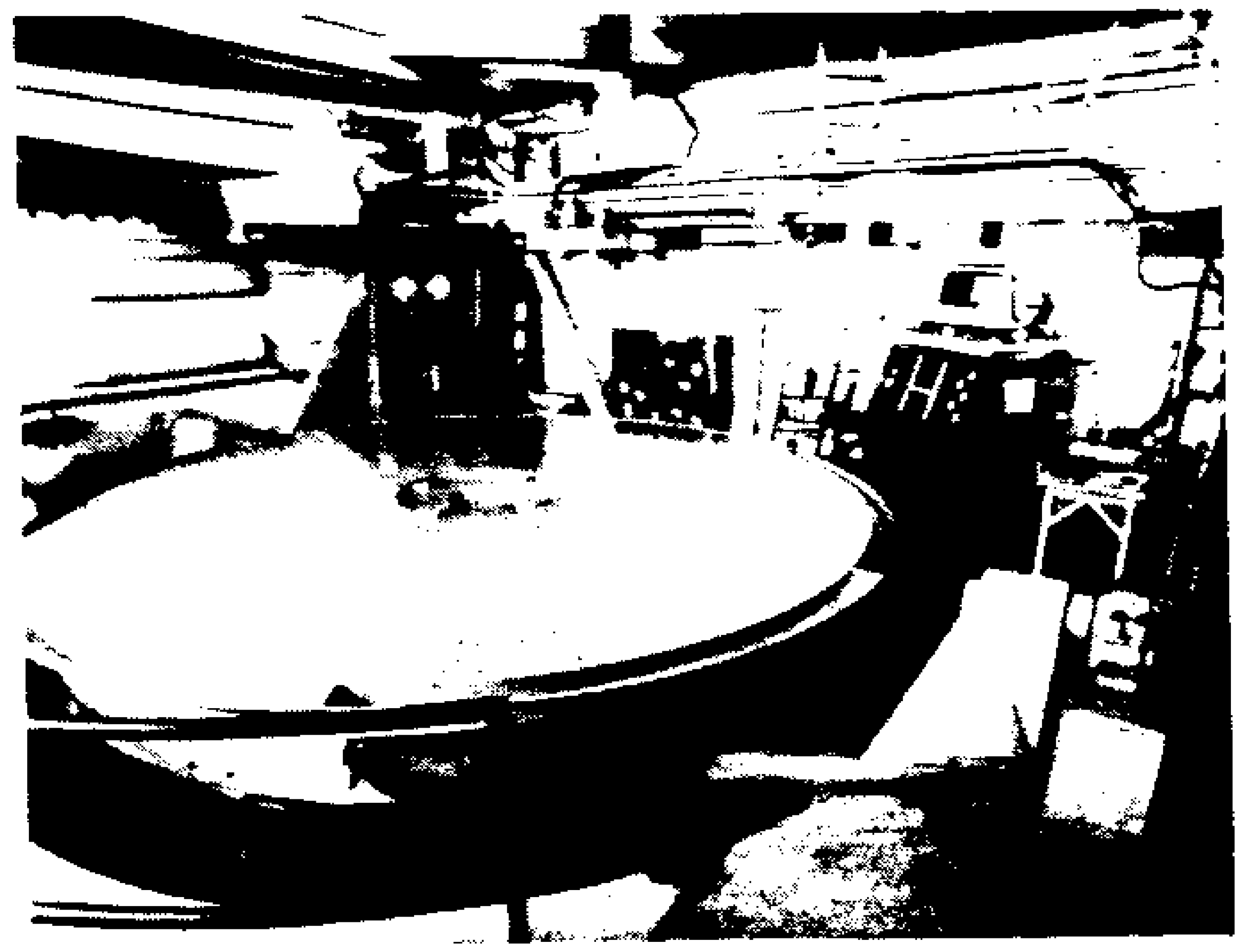

Figure 2. The 4-m polishing machine is hydraulically driven and located in a below-grade room.

## 3. MEASURING THE BLANK

Before any work was done to the blank, we decided that an extensive series of measurements would be made to certify the quality and uniformity of the casting. A special long-armed dial caliper was made and used to measure the thickness of the 804 rib segments at four different heights. Several different lengths of tips were available to accommodate the small spaces in the partial cores. The outer wall thickness was measured at four heights and 60 different azimuth positions, and the thickness of the inner wall at three heights for 18 different azimuth positions. The back plate thickness was measured at each cell around the inner and outer diameters of the blank. Three micrometer caliper measurements were taken and averaged for each hexagon because the as-cast surface was rough. These measurements were summarized in a previously published paper [2] and, in general, the geometric accuracy of the blank was excellent.

## 4. GENERATING THE BACKPLATE AND EDGING THE INNER AND OUTER DIAMETERS

After centering the blank with a dial indicator, the backplate was generated using a 30-cm diameter, 60-grit, metal-bonded diamond wheel mounted on a 5-hp generating spindle. The wheel turned at 1750 rpm producing a nominal cutting speed of 5500 surface feet per minute (sfpm). The coolant was Uniflo coolant oil, from Universal. It was mixed 1 part oil in 20 parts water and recirculated by a Myers submersible pump. The coolant was directed through a tapered brass nozzle with enough velocity to adequately bathe the active cutting area. To prevent the hollow mirror structure from filling up with coolant, 294 rubber stoppers were pressed into the holes in the backplate. They were made by cutting disks out of 12-mm thick rubber sheet.

After the first generating cut across the backplate, it was checked for flatness using a 1.5-m straightedge and shims. We found a conical surface had been generated because the rotation axis of the mirror and table was tilted with respect to the motion of the Pittman arm. The tilt of the polishing table was adjusted and the second cut was made. Following a second tilt adjustment the table was locked in position and the remaining cuts were completed. Measurements showed that about 5 mm of glass was removed from the back surface in three cuts.

A new 220-grit fine diamond wheel with a 45° bevel was used to clean up the casting marks on the rib wall inner diameter. The generator spindle could only reach halfway to the bottom and we decided to continue this cut after flipping the mirror over for front faceplate generation. The bevels, inner diameter, and outer diameter of the backplate were generated in one set-up, to maintain concentricity.

After generating, the holes in the backplate had sharp edges. Each hole was first beveled using a specially made compressed air-driven beveling grinder using a diamond wheel. The bevels formed by this tool were somewhat irregular because the guide rollers rode on the rough, as cast, inner wall of the hole. Each of the 294 bevels was finished by loose abrasive hand grinding for about five minutes with a hemispherical cast iron tool and 80-grit silicon carbide. On completion of the hand grinding, the nominal width of each bevel was 7.6 mm (0.300 inch).

## 5. GRINDING THE BACKPLATE AND OUTER EDGE WALL

The flatness and surface finish of the backplate was improved by loose abrasive grinding with a 1.4-m diameter tool. The tool was borrowed from the University of Arizona Optical Sciences Center and because the existing square quarry tiles had been worn thin, they were replaced with 90 new, beveled tiles, each having a 10-cm diameter face. These white ceramic tiles were made as a special order item for NOAO and have been used successfully on many large grinding tools.

Two sizes of silicon carbide grit were used to grind the backplate, first 80-grit followed by 220-grit. The sidewall of the mirror blank was ground at the same time using a flexible, perforated, stainless steel band held in tension around nearly one quarter of the circumference. The top and bottom of the band were shaped to match the radii of the fillets between the edge wall and the faceplates. As the abrasive from the backplate washed over the outer edge it ran between the sidewall and the perforated band allowing both surfaces to be ground simultaneously.

After each grinding run, the quality of the grind was inspected and flatness measurements were made with a bar spherometer. Additionally, the 1.5-m straightedge and a variety of shims were used to gauge the flatness over a longer baseline. To check for residual cone error from generating, the measurements with the straightedge were taken in both radial and tangential directions. Final measurements showed the backplate was flat to about 60 microns over the full diameter.

## 6. ETCHING THE BACKPLATE

After the backplate was ground sufficiently flat, it was etched with 5% hydrofluoric acid. This was done to strengthen the blank by blunting the tips of microscopic subsurface cracks that occur during the grinding process. A rubber strip was clamped to the outer edge of the mirror blank with a steel banding strap and another was clamped to the inner edge with a rigid steel ring. After taking extensive precautions to protect personnel and equipment, the back surface of the mirror was flooded with 50 gallons of acid forming a pool about 20 mm deep. Although we had previously tested the edge seals, minor leaks developed along both the inner and outer diameters. The acid that leaked around the outer diameter was spread over the outer wall by wiping with a sponge. Ground glass witness samples were placed on several of the rubber stoppers and were later removed for examination. After one hour, the acid was neutralized in place by adding large quantities of dilute sodium hydroxide and monitoring the pH with a hand-held meter.

## 7. FLIPPING THE MIRROR OVER TO THE FRONT SIDE

Before flipping the mirror, we prepared the parts necessary to expand our support from three to nine points. Based on our finite element model, the peak-to-valley deformation of the front surface on the nine-point support would be about 2 microns. We felt this level of deformation would be entirely satisfactory for the generation of the front surface. Nine nylon pucks were glued with contact cement to the backplate (each at the junction of three ribs) and to 1-inch thick, triangular, aluminum spreader plates. Rubber-capped C-clamps provided additional compression to ensure the spreader plates would not slip when the mirror was suspended vertically.

The handling band was put in place around the mirror and secured. The two edge arcs near the top of the mirror were removed to allow the mirror to be lifted away from the table after it was tilted up. A 10,000-lb. capacity Hydra-set was attached to the spreader bar to monitor the distribution of weight supported by the crane and by the supports on the polishing table. By continuously jogging the crane upward we were able to control this distribution as the polishing table was tilted. After the mirror blank was clear of the table, it was brought upstairs and inspected while the three main support points were relocated on the polishing table. The blank was then rotated and placed on the table, face up, following the reverse procedure.

## 8. GENERATING THE FRONT FACEPLATE

Before we could begin generation of the front face we adjusted both the centering and tilt of the blank about the axis of the polishing table. This was complicated because the front faceplate was still as cast and we were required to reference our measurements to the backplate, which was constrained by the four edge arcs. Two kinematically mounted dial indicators were attached to a vertical support clamped to the overarm of the polishing machine, and this allowed intermittent measurements of the tilt and centering as the polishing table rotated. Although this procedure was time consuming, it was possible to adjust both the tilt and centering to 0.003 inches, total indicator runout.

The outer diameter of the mirror was generated first using a 12-inch diameter, 60-grit wheel. The wheel was slowly moved toward the glass 0.083 inch until its upper edge was in continuous contact with the lower edge of the front faceplate. The wheel was then moved upward 0.025 inch per revolution until its lower edge cleared the top of the faceplate. A temporary bevel was generated on the faceplate by locating the lower edge of the wheel 0.300 inch below the top lip of the glass and then moving the wheel up and in using 0.006 inch steps per revolution. A similar process was used to bevel the lower edge of the front plate.

The next generating operation was to cut a flat annulus around the edge of the front surface of the mirror. This flat surface allowed the generator wheel to "feather out" when completing each generating cut of the curved mirror surface, avoiding the risk of chipping. To cut this flat, the generator head was tilted 0.8 degree to provide relief under the diamond wheel. Five passes were required to cut the flat, averaging 0.100 inch per pass. The feed rate was 0.033 inch/minute, with a glass removal rate of 1.4 cubic inches/minute. During this process the bevel that was on the top of the faceplate was lost and a new one was made by the same process. At this point, the thickness of the blank was measured at six locations on the outer diameter and was found to be 18.2655 inches +/- 0.0005 inch.

Before generating the front surface we determined the radius of curvature to be used for the generator control program. The paraxial radius of the hyperboloid is to be 12.250 meters and our optical designer calculated a radius of 12.317 meters for the best fit sphere. We chose to generate a sphere of 12.417 meters (about 100 mm longer than the best fit sphere) because we felt the sub-diameter tool grinding that was to follow would decrease the radius by nearly that amount.

The cut on the front surface started at the inside diameter and spiraled outward as the mirror blank rotated. The initial depth of cut at the center was 0.060 inch and the radial outfeed was at a maximum of 6 inches/hour. The generating progress was monitored on a computer terminal, comparing the height of the wheel against the programmed position. The generator was made to follow the programmed curve by jogging it upward in 10 micron steps at 10 second intervals. We were encouraged to note that the spin-cast surface of the blank matched the required mirror curvature within about one millimeter peak-to-valley. The glass removal rate was kept nearly constant at 1.2 cubic inches/minute by gradually reducing the radial outfeed as the cut progressed. The thickness of the front faceplate was measured with an ultrasonic micrometer at forty locations after the first cut was completed.

The second and third cuts were 0.100 inch deep and the glass removal rate was increased to about 2 cubic inches/minute. The generating proceeded well until a lightning-caused power outage stopped the third cut with about 0.5 inch left in the radial direction. We decided not to try to finish the cut but instead leave the 0.050 inch step to be cleaned up with the fourth and final cut. The first radius of curvature measurements were made using a 34.720-inch diameter, three-ball spherometer (called the Kraft spherometer) borrowed from the University of Arizona Optical Sciences Center. The measured radius was nominally correct and we prepared to make the final cut, 0.115 inch deep. We followed the same prescription used for the 0.100 inch cuts except the radial outfeed was slowed to 1 inch/hour when cutting through the step left from the previous cut. After measuring the front faceplate thickness, we found an average of 0.330 inch material had been removed during the final three cuts.

The fine diamond (220-grit) wheel was mounted to the generator and we proceeded to touch up the outer diameter and bevels. The inner diameter was measured to be 37.510 inches and we decided to make it the same as the inner diameter on the backplate, 37.770 inches. The fine wheel was used to remove the required material and the bevels were also formed at this time. The final cut made with the generator was to clean up the inner cylinder wall and to match that cut with the one started from the backside. After this cut was completed, the generator was removed from the machine to prepare for loose abrasive grinding of the front faceplate.

## 9. GRINDING THE FRONT FACEPLATE

The grinding of the front faceplate was done exclusively with a 1.5-m diameter aluminum tool covered with ceramic tiles. This tool was specially designed to be both lightweight and stiff, and consisted of 1.5-inch thick aluminum plate bonded to a 5-inch thick aluminum honeycomb core. The bottom plate had been previously machined to a convex radius of 380 inches for use on a smaller mirror. The flange from the polishing machine spindle bolted directly to the bottom plate. The side and top were clad with thin aluminum sheet to provide a smooth, easy-to-clean surface.

The convex surface of the tool was covered with nearly 100 ceramic tiles of the same type used for the flat tool during backplate grinding. The tiles were waxed onto the tool using a stiff blocking wax after warming both the surface of the tool and the tiles. Partial tiles were used to fill in voids around the edge. The radius of curvature of the tool was about 100 inches too short for the 3.5-m mirror and, as Figure 3 shows, we provided a better match by cutting the surface of the tiles using a separate generator. After generation, the tool weighed 500 lbs. and the surface area of the tiles was calculated to be 1445 square inches.

Grinding on the front faceplate using 80-grit silicon carbide commenced on November 3, 1989. After the first two hours of grinding most of the surface was lapped, except for three concentric rings that were attributed to errors in the Pittman arm rollers during generation. The first check of the radius of curvature using the Kraft spherometer showed that the surface was between two and three inches longer than the target radius.

The mirror was ground with 80-grit for 28 hours total and about 1.9 mm of glass was removed. This corresponds to an average material removal rate of 70 microns per hour. During 21 of those hours the pneumatic cylinder normally used to lift the tool was pressurized to increase the tool pressure to 0.9 psi on the mirror surface. After 27 hours of grinding the tiles of the tool had worn thin enough that it was necessary to retile the tool before proceeding with the finer grits. The old tiles were stripped off, new ones waxed into place, and the tool was generated to the proper radius as before. To ensure the new tile surface matched the mirror, the tool was used for one hour with 80-grit. Spherometer measurements showed the mirror radius to be about 1.9 inches longer than the desired radius.

After the 80-grit grinding was completed, the mirror, grinding tool, machine and room were thoroughly cleaned. Grinding continued with 220-grit silicon carbide for 17 hours, resulting in the removal of about 0.48 mm of glass. During all five grinding runs the weight of the grinding tool and spindle were brought to bear on the surface with no additional pressure from the pneumatic cylinder. The pressure of the 1.5-m tool on the glass was about 0.6 psi and the average material removal rate was nearly 30 microns per hour. Measurements with the spherometer showed the radius of curvature was about 0.5 inch longer than the nominal value.

On completion of the 220-grit grinding an extensive clean up was performed that included the replacement of the outer plastic skirt. Because of the difficulties in fitting the inner skirt and making it watertight, it was not removed. Instead, it was thoroughly cleaned in place and sprayed with a clear acrylic paint to seal in any remaining grit. As the surface of the grinding tool was worn off, we noticed some cracks and small voids had appeared in several of the ceramic tiles. Because the cracks were possible sources of contamination, they were enlarged using a small hand grinder, thoroughly cleaned, and sealed by painting the tiles with shellac. During the later stages of grinding the largest voids were filled with epoxy.

The next stage of grinding was done using 25 micron aluminum oxide (see Figure 4). The amount of time spent grinding was 23 hours and during the first 13 hours the pressure of the tool on the glass was 0.6 psi. By using the pneumatic cylinder on the spindle, the grinding pressure was reduced to about 0.5 psi during the last seven hours of 25 micron grinding. About 0.25 mm of glass was removed and the average material removal rate was just over 10 microns per hour.

Spherometer measurements showed the radius of curvature to be only 1.5 mm longer than the design value.

We decided that the smallest grit that would be used for grinding would be 9 micron aluminum oxide because the risk of scratches from using a finer grit outweighed the length of time spent polishing from a coarser surface. The 9 micron grit was used for 20 hours with a grinding pressure of 0.5 psi. An average of 76 microns of glass was removed and the average removal rate was nearly 4 microns per hour. The radius of curvature appeared to be less than 2.5 mm too short when the 9 micron grinding was completed. After completing fine grinding, we made measurements of the faceplate thickness over each of the 294 cores using an acoustic thickness gauge. The front plate thickness varied from 27.18 to 31.95 mm with an average thickness of 30.14 mm.

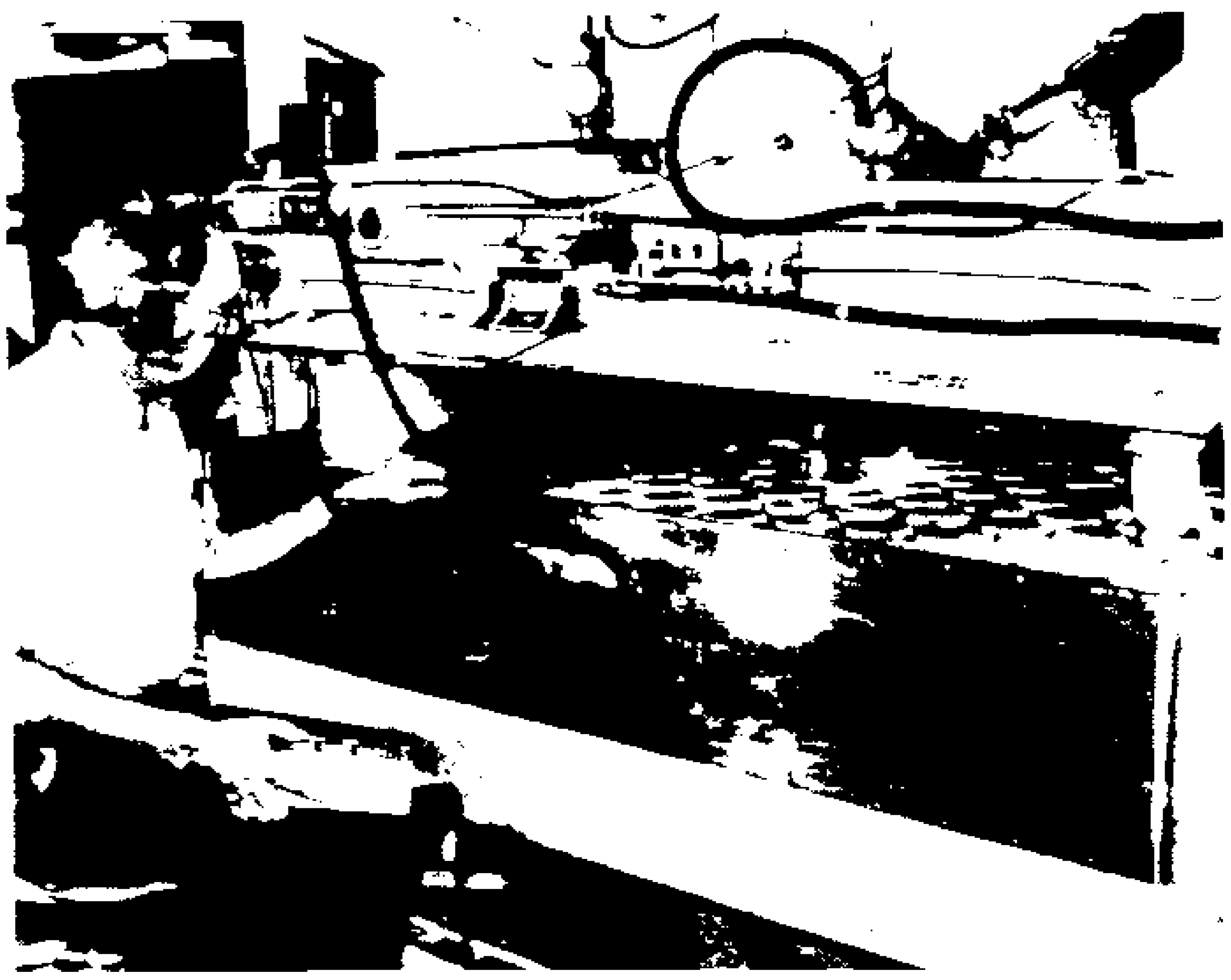

Figure 3. The radius of the 1.5-m grinding tool is cut on a separate generator following a curved template.

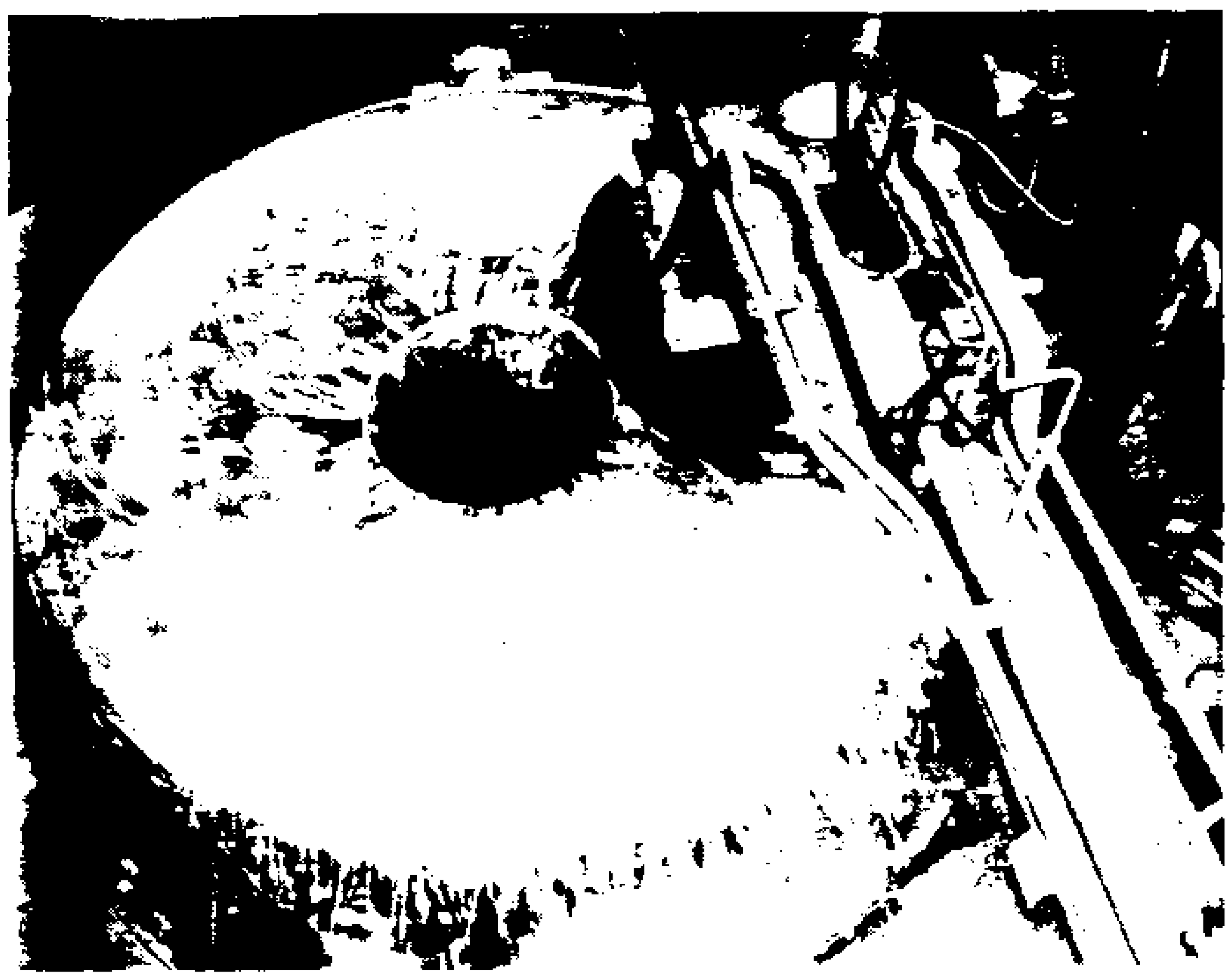

Figure 4. The front plate is ground with 25 micron aluminum oxide and the 1.5-m grinding tool.

## 10. POLISHING AND TESTING THE FRONT FACEPLATE

After the completion of grinding, we did an extensive cleanup of the mirror, the tool, the polishing machine, and the polishing room. The inner and outer plastic skirts surrounding the mirror were removed and discarded. The polishing room and machine were hosed down and wiped from top to bottom. The grinding tool was scrubbed and hosed off several times, followed by heating the wax around the tiles with a propane torch to seal in any remaining grit. Additionally, all tools and instruments that were used during grinding were carefully cleaned.

The 1.5-m polishing lap was prepared by pouring about 6 kilograms of molten Gugolz #73 pitch onto the individual ceramic tiles. By carefully pouring just the right amount of pitch onto each tile, we were able to form a uniform, 0.25-inch thick layer with little spillage. The result was a lap with circular facets packed together in a hexagonal arrangement with large gaps between them. We chose not to remove the tiles from the tool because the mismatch in radius between the aluminum surface of the tool and the surface of the mirror would have resulted in an unacceptable variation in the thickness of pitch. For the same reason, we decided not to cover over the tiles and the space separating them with a thick layer of pitch. After the lap was pressed out, it maintained its shape well and required little trimming.

On February 8, 1990, the first polishing run was made using the 1.5-m lap for three hours. The polishing pressure on the glass was 0.6 psi and the polishing compound was Rhodox #76, a 3-micron size cerium oxide. Three more hours of polishing were required to improve the surface reflectivity to the point where optical tests were possible. Initial tests with the scatterplate interferometer revealed a highly distorted surface with between 30 and 40 waves of astigmatism. The astigmatism was aligned with the direction of the edge arc clamps used to secure the mirror during generating and it appears likely they were too tight. Additionally, a Foucault tester was set up that allowed us to cut the return beam in two directions.

The difference between the two foci was measured to be 1.4 mm and this corresponds to a delta sag of 21 microns, which equals 33 waves (over the entire surface) at the He-Ne wavelength of .6328 microns. The radius of curvature at best focus was measured directly with a steel tape and we found it to be 8.4 mm longer than the nominal 12317 mm. This difference between the steel tape and the spherometer can be accounted for by considering the fractional precision of the Kraft spherometer, which was 0.1% for this mirror.

After unambiguously identifying the high and low quadrants on the mirror by using the Foucault tester and the scatterplate interferometer, we began polishing the high sectors with a 0.6-m diameter tool. The tool was an aluminum disk, machined to the proper convex radius, covered with molded 2.5-inch pitch squares. The squares were molded from Gugolz #73 pitch with a small amount of pine tar added to slightly soften the pitch and enhance its ability to accept the polishing compound. Thirteen hours of polishing was equally divided between the two high sectors during six separate runs. The peak-to-valley astigmatism was reduced to 26 waves and, at that point, we were able to secure reducible photographs through the scatter-plate interferometer. The interferograms were recorded on 35-mm film, enlargements were made, and the prints were manually digitized using the WISP interferogram reduction package distributed by WYKO.

After monitoring the progress with the 0.6-m lap, we felt that we could improve the removal rate by using the larger, 1.5-m diameter lap. The changeover was straightforward, but we spent some additional time pressing out the large lap to ensure a good fit to the glass. The pneumatic cylinder that normally carried the weight of the tool was pressurized to allow an increased polishing pressure of about 1.0 psi. This method, combined with localized polishing on the high sectors, reduced the peak-to-valley from nearly 23 waves to just over 8 waves in eight hours of polishing. We were somewhat surprised to find the resultant removal rate was nearly $2\lambda$ per hour. The negative aspect of the sector work was that it had introduced a slight dip in the middle of each sector, thereby creating four high spots. We were gratified to see the rapid material removal, but we were concerned about the controllability of the process and decided to try a different method. The new approach was to run the polishing lap over the entire mirror and increase the pressure as the high spots passed below. This method was used for six hours in four runs of equal length. The high lobes were marked on the outer diameter of the mirror using strips of colored tape. When those areas passed beneath the lap, the valve controlling the pneumatic cylinder was manually opened, and the pressure of the lap on the mirror quickly increased from about 0.6 psi to nearly 1 psi. Similarly, the valve was closed as the lap passed over the low areas. We found this method, while being conceptually attractive, did not yield a reasonable convergence and the peak-to-valley error increased slightly.

We returned again to the method of sector polishing and used it in spite of the tendency to produce a dip in the middle of the sector. We attempted to offset this tendency by increasing the width of each sector from 80° to 120° and slightly modifying the stroke. After four hours the peak-to-valley errors were reduced from $9.2\lambda$ to $6.4\lambda$. There were now three high spots near the outer edge and a prominent hill surrounding the central hole. The three spots were polished for an hour each, as sectors, without any additional downward pressure. The central hill was worked separately for one hour by shortening the strokes, moving the offset inward, and counter-rotating the lap against the area. Following these three hours of polishing the peak-to-valley error was $4.5\lambda$.

The results of working on the central hill were encouraging and we extended the strategy of counter-rotating the lap against high areas to enhance the polishing action. This was done by counter-rotating the lap against the outer diameter in the north and south quadrants and similarly against the inner diameter in the east and west quadrants. Additionally, we decided to try an experiment and stop the table rotation when the lap was over the east and west quadrants. This allowed the lap, which was rotating and stroking, to dwell on each quadrant 25 percent of the time. The polishing run lasted two hours, and the knife-edge test immediately afterward showed two distinct, symmetrical "craters", complete with central mountains. By stopping the table at nearly the same position each time, we had broken one important rule of polishing - keep the stroke random. The surface was noticeably rougher and we decided to proceed immediately with a 1.5-hour long smoothing run. Data reduction after this series of runs showed a peak-to-valley error of $3.5\lambda$.

At this point, the size of the high areas and the overall surface error had been reduced to where we felt the 0.6-m diameter lap would be more effective. Several different polishing strategies were used with the 0.6-m lap. The first was to sweep the smaller lap over the central area of the mirror while manually varying the polishing pressure. The polishing pressure was 0.5 psi when the lap was over the low areas, and it was increased to 1.4 psi while over the high areas. This method was used for only two hours. The second strategy was to use the lap on individual sectors (at one time as many as five) using the aggressive polishing pressure of 1.4 psi. After nearly 8.5 hours, in seven individual runs and several intermediate interferometric tests, the peak-to-valley error was reduced to 2.1λ and the rms error was 0.27λ.

During this phase of polishing there was a considerable effort to implement the CCD scatterplate interferometric testing using the Roddier/Fox software for data reduction.[3,4] The limitations of the software require that the total peak-to-valley error be less than about three waves and the surface be smooth with no large slope errors. Although our surface met the first criteria, it failed the second, particularly near the edge. In an effort to smooth the overall surface and correct the turned up edge, we decided to switch back to the 1.5-m lap and use a neutral stroke with a much lighter polishing pressure of 0.4 psi. The first run of four hours was successful in smoothing the surface and it seemed that the edge was also improved. Unfortunately, because we were in the process of changing test methods, we overlooked that the edge was beginning to roll off downward. The second run was identical to the first and after six hours the edge was unmistakably turned down and the peak-to-valley error increased slightly to 2.3λ. The surface of the mirror was smooth enough to allow consistent phase measurements using the Roddier/Fox software if the clear aperture of the CCD interferogram was reduced by three pixels (about 3 cm on the mirror). This dramatically decreased the time between polishing runs by eliminating the photographic processing and manual digitizing of interferograms using the WISP software package. The polishing strategy was changed to reflect this improvement. Using the high resolution data from the CCD scatterplate test it was possible to accurately transfer a contour map of errors to the surface of the glass using the hexagonal grid as a guide (see Figure 5). The 1.5-m lap was replaced with a 0.4-m lap and Figure 6 shows that it was "driven" over the high areas using a technique similar to that of computer-controlled polishers.

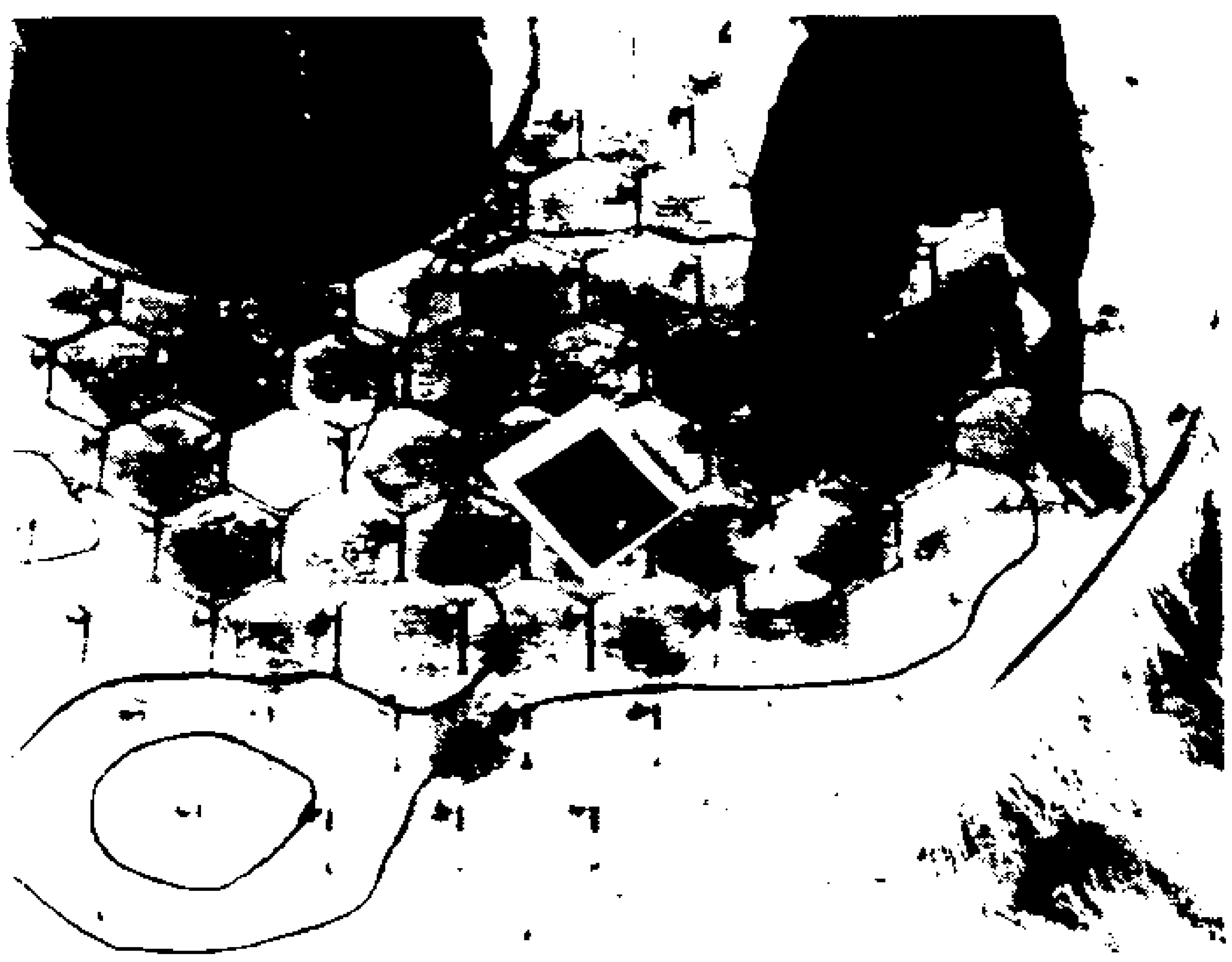

Figure 5. The optician transferred the error map directly to the surface of the glass using the hexagonal grid as a guide. The contour step size is 3/8 wave.

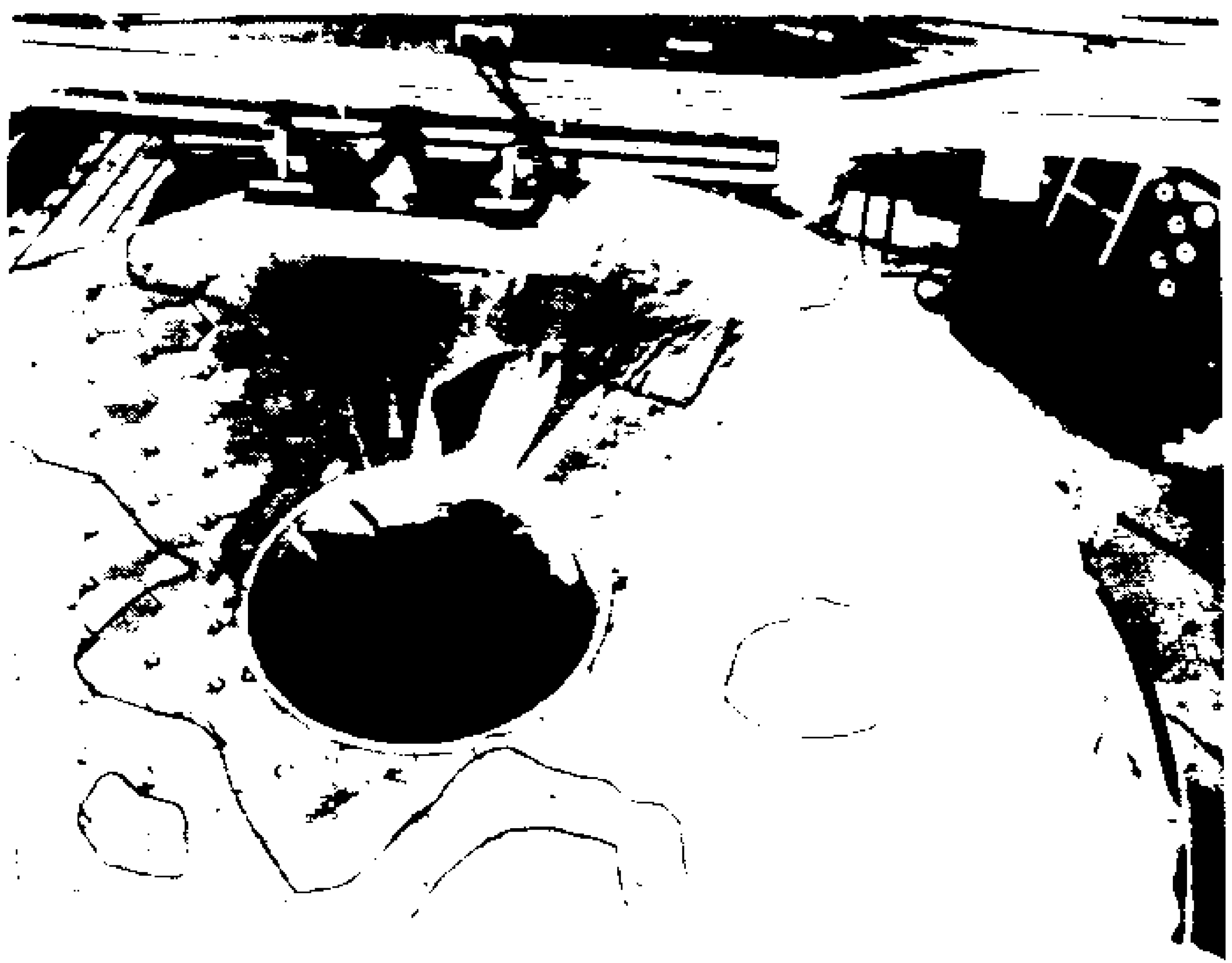

Figure 6. The position of the 0.4-m diameter lap was manually adjusted to dwell over the high areas.

The dwell time was based on surface height and the small size of the lap made it possible to follow the complex contours. To control the lap position manually, the table rotation was adjusted to be slow - about one revolution every thirteen minutes, while the stroke was set to be fast and short - over 9 strokes per minute with about a 6 centimeter amplitude. The radial position was adjusted using the fast and slow speeds on the slew motor driving the Pittman arm. Additionally, the lap was driven in rotation at 2 rpm. The polishing pressures used were high and ranged from a minimum of 2 psi to a maximum of 4 psi.

After several runs with the 0.4-m lap, we decided to extend the method and use the 0.6-m lap to cover broader areas. Because of the small size of the laps, it was possible to use one lap while the other was cold-pressing on another part of the mirror. This method of localized polishing, while being both conceptually simple and easy to implement, showed good convergence as the peak-to-valley error was reduced from 2.3λ to 1.0λ during seven polishing and testing cycles. The actual time spent polishing during these seven cycles was 11.5 hours. Three more iterations were made using this method and the surface errors remained the same or increased slightly. Later examination of the optical test data showed that inconsistencies because of thermal effects had adversely affected polishing decisions. Because progress with the small laps had ceased, we decided it was an opportune time to reinstall the 1.5-m lap to work on improving the outer edge. The lap was used to wear down the inner portions of the mirror and thereby bring up the edge.

During large tool polishing, a series of simultaneous optical and thermal tests were obtained that allowed us to address the cause of the figure changes that appeared unrelated to polishing. The thermal data from 960 thermal sensors attached to the mirror was input to a finite-element model of the mirror. Contour maps of thermal difference deformations were compared to corresponding optical test differences. Our structural engineer performed the finite-element analysis and his results showed that most of the figure changes during optical testing were correlated with temperature variations in the mirror.

We also noted that the figure of a borosilicate mirror is influenced by the thermal conditions during polishing. The most prominent effect occurs when the outer edge is dry and warmer than the front surface, causing the area around the edge to expand and be preferentially polished. When the mirror returns to a uniform temperature, the edge appears to be rolled off downward. To counteract this effect during the large tool runs, we sprayed the outer edge with water mist to keep it closer to the surface temperature by evaporative cooling. The polishing pressure was 0.35 psi for the first two hours and then decreased to 0.21 psi. before the next twelve hours of polishing. Although some progress was made by varying the stroke parameters and lap rotation speed, it became apparent to us that it was necessary to reduce the size of the lap. The pitch covering several outer rows of tiles was removed, forming a hexagonal-shaped lap 1.3-m across. The lap was used in this configuration for about ten hours until we felt the outer edge had been sufficiently corrected. The last hour was spent polishing the east and west 90° sectors with little improvement. At this time, because of the consistent optical test results and the finite-element analysis done earlier, we believed the high east and west lobes were real errors on the surface that were enhanced by a particular temperature distribution within the mirror. Our decision to switch to the 0.4-m lap and begin the process of final figuring was influenced by this belief.

## 11. FINAL FIGURING AND THERMAL CONTROL

With the turned down edge sufficiently corrected by use of the large tool, we decided to return to the strategy of localized polishing with small laps. The high lobes were marked out, and the 0.4-m lap was used for one hour on each lobe, followed by an additional 30 minutes on each with the 0.6-m lap. Again, as before, the polishing pressures were high - 2.8 psi for the 0.4-m lap and 0.7 psi for the 0.6-m lap. The first CCD scatterplate test performed 18 hours after the polishing run showed a peak-to-valley error with astigmatic tendencies of $1.1\lambda$. Six hours later, in the same day, a second test was performed and the surface errors, particularly near the east and west edges, were reduced about $0.1\lambda$. We were encouraged by this result and decided to continue testing while further stabilizing the mirror temperatures during the next several days. Efforts to stabilize the temperatures ranged from changing the orientation of the mirror relative to the air-handler vents in the room to turning off the air handlers completely and letting the mirror "soak" in ambient air. The effectiveness of these methods was difficult to judge based on optical tests alone. We noted that as the mirror continued to stabilize in temperature, the mirror figure generally improved and stabilized. However, it is important to remember that figure stability does not necessarily imply a complete absence of thermal distortion. The last test in this series was performed 114 hours after the polishing run and the peak-to-valley error had been reduced to $0.76\lambda$. Additionally, a major component of the thermal distortion, low order astigmatism, was non-existent. Three additional polishing runs, for a total of 120 minutes, were made with the 0.4-m lap. One of those was a rotationally symmetric run to correct a minor high ridge at the 50 percent zone.

At this point, our test results showed we needed to wait at least two days between polishing and testing to get the figure stability needed for final figuring. The interval was often lengthened because the cold pressing of laps locally affected the heat exchange of the front faceplate and therefore had to wait until after testing was complete. Air turbulence in the optical path became more of a problem during final figuring and we installed an insulated shroud to minimize it. This immediately improved our optical testing repeatability and accuracy. We measured the amplitude of the print-through and found it to be 30 nm on average, with some cells as high as 50 nm. Based on this information, we again reinstalled the 1.5-m lap in an effort to reduce the amplitude of the quilting.

After nearly six hours of polishing with a lap pressure of about 0.25 psi we achieved the milestone of meeting the original specification of 50 nm rms. CCD scatterplate interferograms showed the peak-to-valley error was $0.67\lambda$ and the rms error was $0.074\lambda$. We felt, however, it was desirable to further improve on the figure because the full aperture had not been tested and a structure function calculation recently added to our analysis program showed a need for improvement at high spatial frequencies. We were concerned that although continued polishing with the 1.5-m lap would probably improve the print-through errors, there was a risk of increasing the low and mid-frequency errors.

To investigate the possibility of individually polishing high frequency errors we prepared a 13-cm diameter polishing lap and selected a row of seven cells in the mirror with print-through bumps ranging in height from 18 to 42 nanometers. These areas were polished by hand, working for one second per nanometer of height. The optical test shown in Figure 7 clearly shows that each bump had been changed into a shallow depression. The material removal rate, using a pressure of about 1 psi, was about 1.5 nm per second. Based on this successful experiment, we decided to polish the print-through bumps over cells that were in high areas on the mirror (see Figure 8). A contour map showing only the high frequency errors was prepared and superimposed with the normal low frequency contour map. This combination was used as a guide to determine the position and length of polishing time for a particular bump. When the run was finished, 163 individual bumps had been polished for an average of 25 seconds each. A two hour smoothing run with the 1.5-m lap immediately followed the hand polishing.

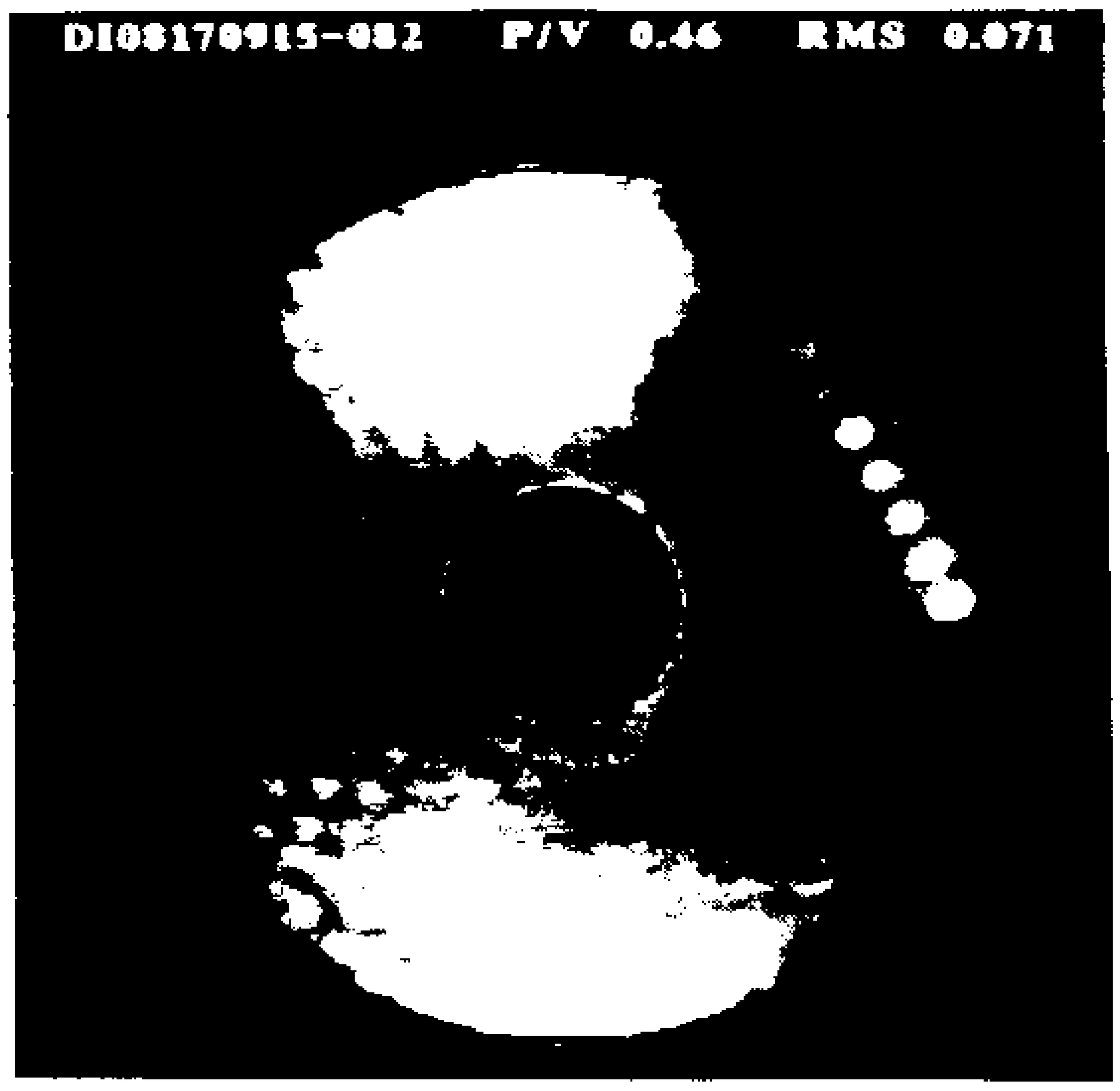


Figure 7. The difference between two phase maps taken three days apart indicates the effect of localized polishing. The seven areas were polished for a time based on their measured heights.

Figure 8. The optician is using a 13-cm diameter lap to remove high spatial frequency errors. With a polishing pressure of 1 psi, the removal rate is approximately 1.5 nanometers per second.

The final polishing run on the mirror used three sizes of laps and was completed in three days. The selection of the lap size was based on the spatial frequency of the error that was to be polished. On August 30, 1990 the 13-cm lap was used by hand to polish the remaining small scale, high frequency bumps. After transferring the contour map to the glass we made a short run using the 0.4-m lap to reduce the mid frequency errors. The last step was three hours of uniform polishing with the 1.5-m lap, using rouge as a polishing compound. Rouge was used because we felt it would remove material at a slower rate and improve the surface finish. Polishing pressure was kept at 0.2 psi with the expectation that any remaining print-through bumps would be further reduced. After the polishing run was completed, the inner and outer plastic skirts were removed, the mirror was cleaned, and we prepared to do the final series of optical tests.

## 12. FINAL OPTICAL TEST RESULTS

After the polishing was completed, we allowed the mirror to thermally equilibrate for 46 hours before performing the first optical test. The mirror was intermittently rotated relative to any thermal inputs within the polishing room, as well as allowed to soak at ambient temperature. A second test was done eight hours after the first, and while it was similar, there were distinct differences, particularly near the outer edge. With the hope of obtaining agreement with either of the first two tests, a third one was done the next day, nearly 16 hours later. It differed somewhat, and we felt we were seeing the optical effects of the thermal interaction between the mirror and its environment.

Shown in Figure 9 is one of 20 interferograms used to calculate the average phase map. This average phase map is shown in Figure 10 and as measured over the full aperture, shows the accuracy of the finished sphere was 0.52λ peak-to-valley and 0.066λ (42 nm) rms. The turned down edge was almost eliminated and a Strehl ratio of 0.55 was calculated from the point spread function. Although there were further improvements that could be made to the surface, work was halted because of schedule constraints. We felt that the surface that was produced would be more than adequate to evaluate the support and thermal control systems during upcoming tests.


Figure 9. One of ten interferograms used to produce the phase maps.

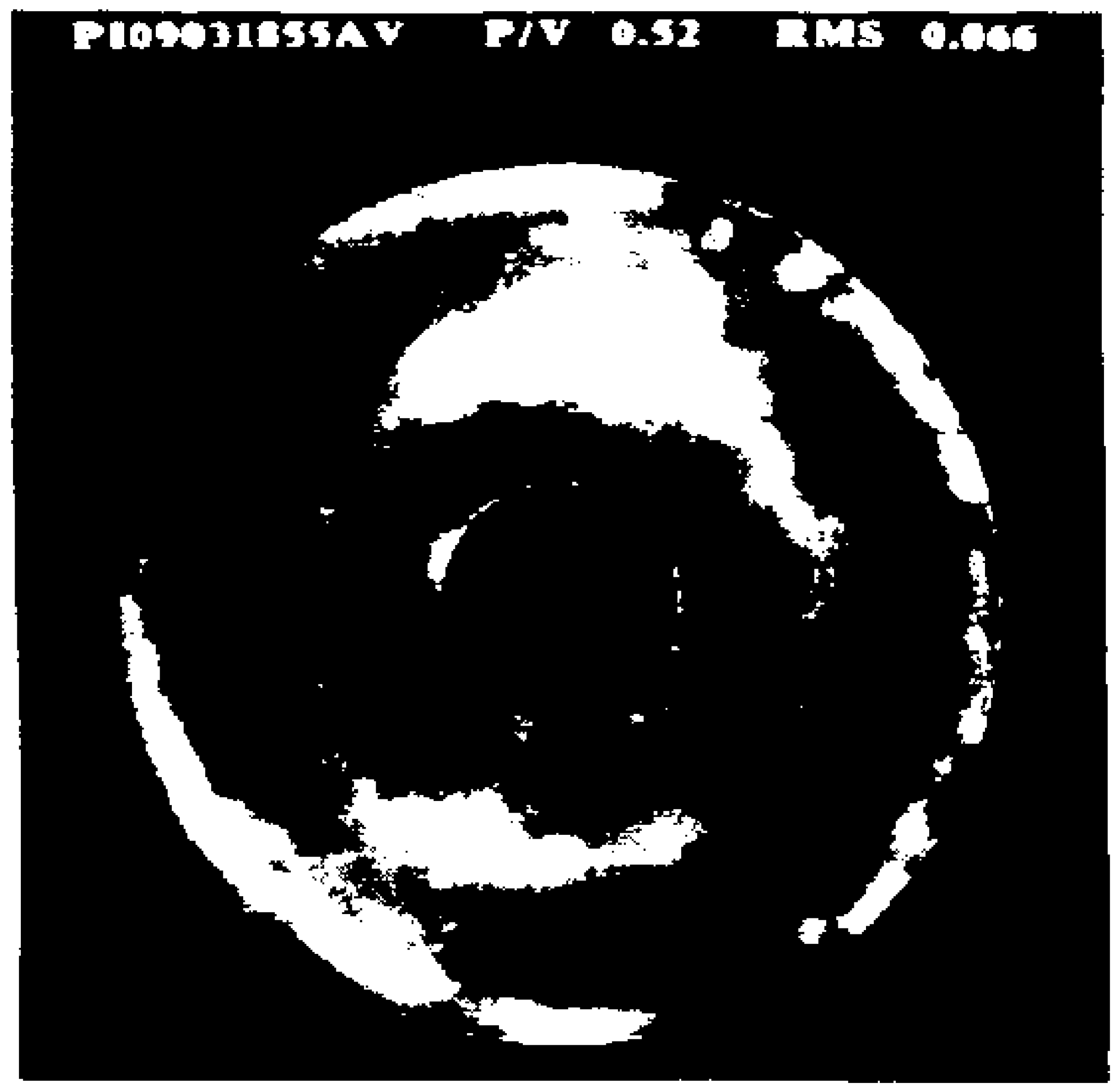


Figure 10. The average of ten phase maps showing the full aperture of the 3.5-m mirror.

## 13. ACKNOWLEDGEMENTS

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