NASA
Technical
Memorandum

NASA TM- 100312

(NASA-TM-100312) A 1987 PROGRESS REPORT OF MANUFACTURING TECHNIQUES FOR GRAVITY PROBE B GYROSCOPE ROTORS (NASA) 32 p Avail: NTIS HC A03/MF A01 CSCL 14B
N88-11101
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1987 PROGRESS REPORT OF MANUFACTURING TECHNIQUES FOR GRAVITY PROBE B GYROSCOPE ROTORS

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Materials and Processes Laboratory
Science and Engineering Directorate

September 1987

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TM-100312	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE 1987 Progress Report of Manufacturing Techniques for Gravity Probe B Gyroscope Rotors		5. REPORT DATE September 1987 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Roy A. Taylor, Ed White, and William J. Reed*		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546		13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum 14. SPONSORING AGENCY CODE E

15. SUPPLEMENTARY NOTES

Prepared by Materials and Processes Laboratory, Science and Engineering Directorate.

*Retired NASA employee

16. ABSTRACT

This report presents the significant improvements in the manufacture of Gravity Probe B gyroscope rotors that have been developed since the publication of the last report on this project [1]. The improvements discussed include the polishing machine structure, rough laps, finishing/polishing laps, lapping procedure, measurement techniques, and a summary of the manufacturing status. These six areas represent significant improvements in manufacturing of the gyroscope rotors which will meet flight requirements.

17. KEY WORDS Gravity Probe B Gyroscope Rotors Lap Finishing Rough Finishing	18. DISTRIBUTION STATEMENT Unclassified — Unlimited

19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 31	22. PRICE NTIS

MSFC - Form 3292 (May 1969)

For sale by National Technical Information Service, Springfield, Virginia 22151

ACKNOWLEDGMENTS

The authors wish to acknowledge the extremely significant contributions of Mr. Wilhelm Angele (NASA retired) for his dedicated direction, designs, and development efforts that provided advancement of the Gravity Probe B Gyroscope Rotor Development Porgram.

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INTRODUCTION

As stated in Reference 1, the first ball lapping machine used by the Materials and Processes Laboratory consisted of four small dc motors mounted so that their shafts rotated in a horizontal plane with the shaft ends pointed toward a common center. The machine is described in detail in Reference 2. The problem with this arrangement is gravity. Since the ball and the laps are pulled down by gravity, the laps have a tendency to lap more at the top of the circle of rotation rather than uniformly over the circle of rotation. To overcome this problem a new ball lapping machine was designed and is described in detail in Reference 1.

The new machine is shown in Figure 1. This machine uses three motors mounted at 120 deg intervals around a circle on the base plate of the machine with their shafts pointing upward at an angle of 20 deg and one motor mounted vertically. A spring loaded rotary lap is fitted on each shaft. The upward thrust vector of the spring loaded laps is adjusted to be equal to the weight of the ball plus the downward thrust vector of the spring loaded lap of the fourth motor which is mounted directly over the top of the ball. Each lap has 4 deg of freedom to follow the contours of the ball.

To produce a uniformly polished sphere/rotor, the entire surface must be lapped an equal amount, or in other words, to cause the sphere to tumble in a uniform manner such that the entire surface receives an equal amount of lapping time. To accomplish this tumbling action, each lap motor direction is reversed by cam-driven reversing switches as discussed in Reference 1 and shown in Figure 2. The four lap machine with the three bottom laps and one top lap was determined to be the best design to produce a consistent round rotor. Using this machine, rotors could be fabricated to within 0.0508 μm (2 μin.) of being a perfect sphere on a consistent basis, but very extreme care was needed to produce a rotor with a sphericity (sphericity is defined to be the maximum deviation from a perfect circle) better than 0.0508 μm (2 μin.). As stated in Reference 1, one limiting factor in fabricating rotors was the ability to measure them to the accuracy required, or for that matter, as good as they could be manufactured.

To solve this problem, a new computerized Talyrond Roundness Measuring Machine (Talynova) was purchased and installed. The Talynova Measuring System, under program control, automatically centers the part, removes spindle errors, and has a roundness accuracy of ±0.005 μm (0.197 μin.).

Although the new four lap polishing machine offered many advantages over the old machine, it was determined that additional improvements were needed to produce rotors to less than 0.0254 μm (1 μin.) of sphericity. Using this machine there are four variables (lap material, lap speed, spring pressure, and lapping compound) that determine the capability to produce spheres to the required

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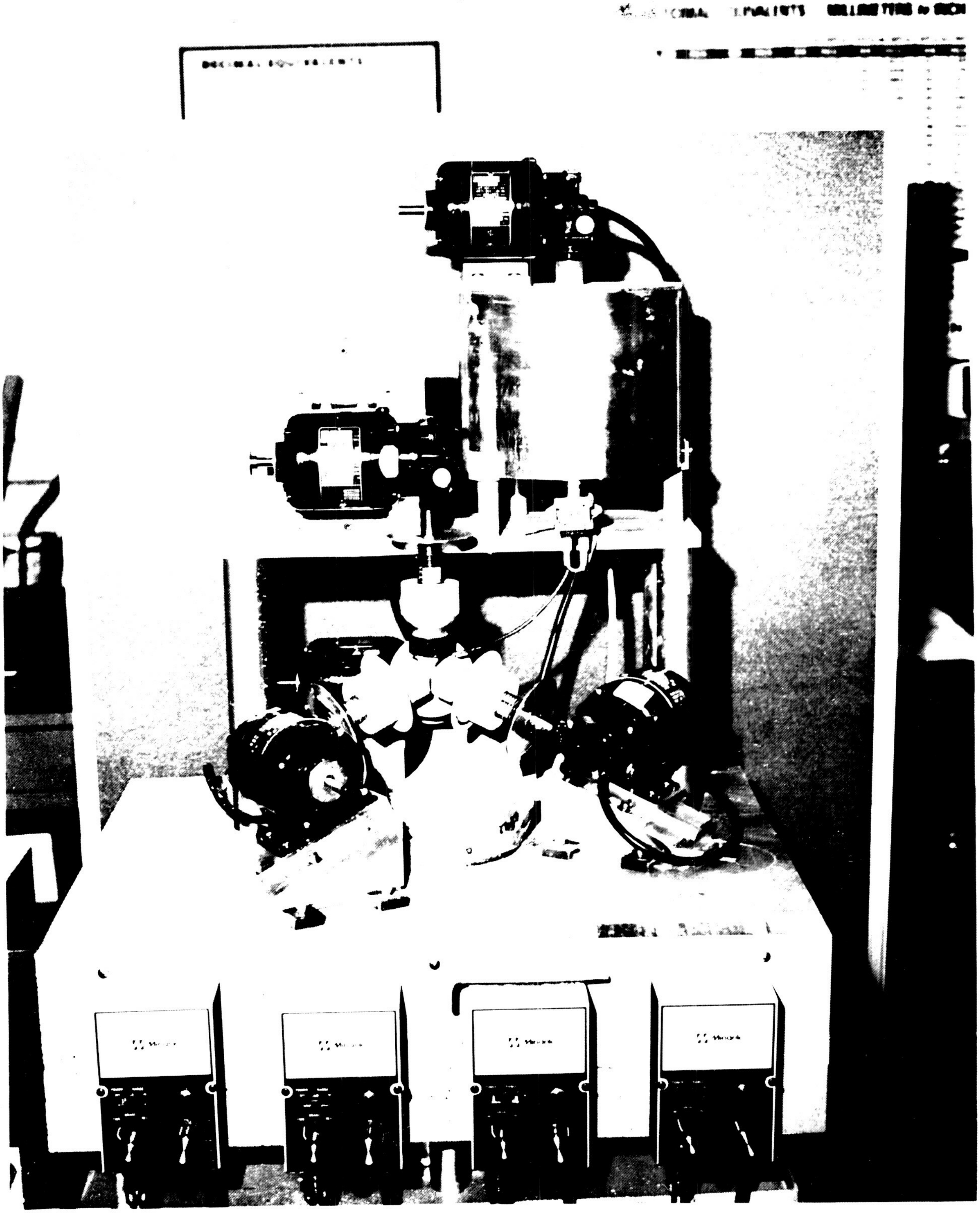

Figure 1. Lap polishing machine.

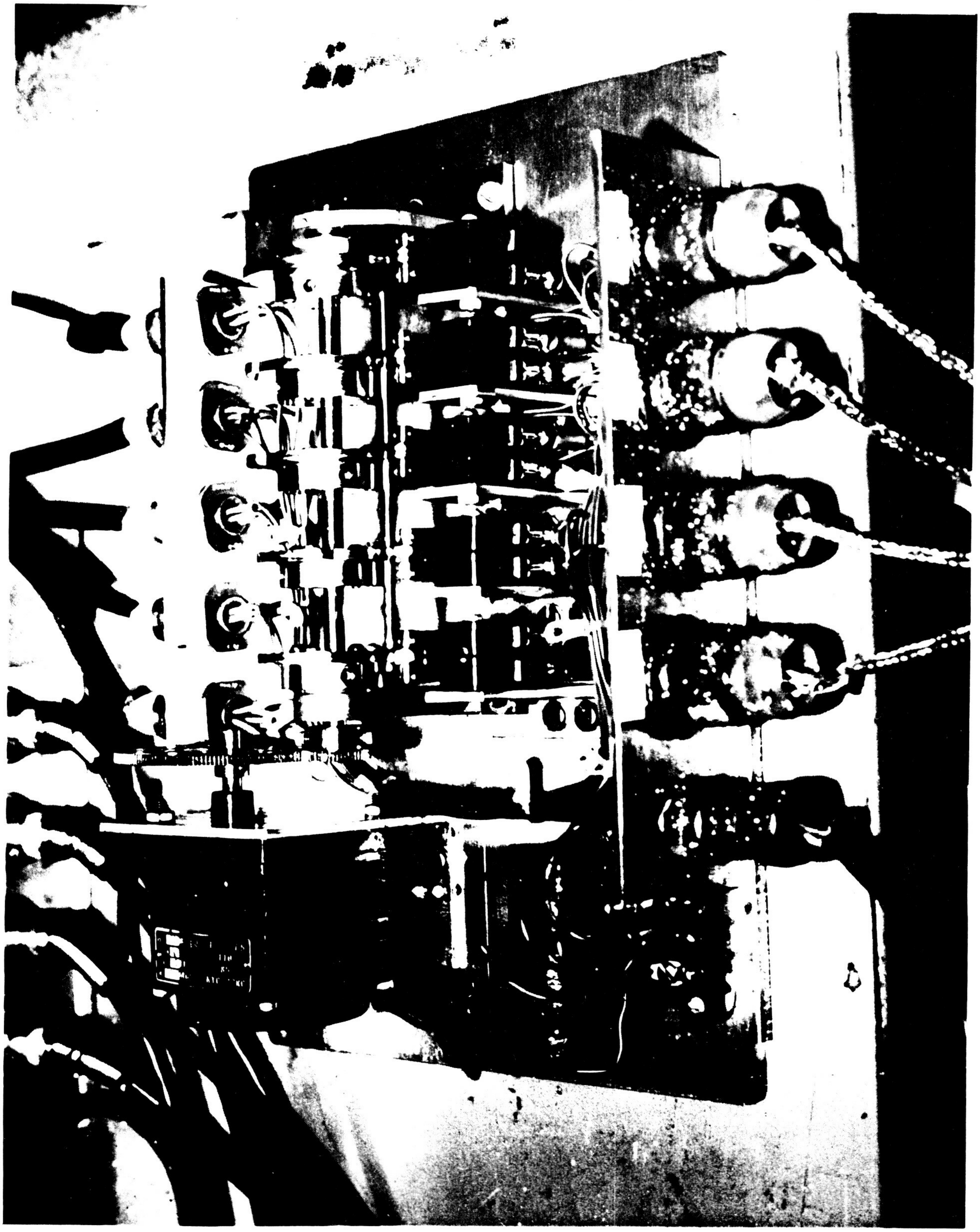

Figure 2. Motor reversing cam controller.

roundness. A program to define the best settings and material for all these variables was undertaken with the following results:

Lapping Speeds:

Rough Laps — 225 rpm

Finish Laps — 125 rpm

Spring Pressure:

Rough Laps — 340 gm, (12 oz.) 1.143 mm (0.045 in.) diameter spring wire for 120 degree horizontal motors.

Rough Laps — 110 gm (3.88 oz.) 0.016 mm (0.040 in.) diameter spring wire for vertical motor.

Wound Spring Dimensions — 2.22 O.D. cm × 6.35 cm long (0.875 in. O.D. × 2.5 in. long) wound with closed (flat) ends.

Finish Laps — 160 gm, (5.64 oz.) 0.940 mm (0.037 in.) diameter wire for 120 deg horizontal motors.

Finish Laps — 62 gm, (2.19 oz.) 0.787 mm (0.031 in.) diameter wire for vertical motor.

Lapping Material:

Rough Laps — Cast iron (Meehanite)

Finish Laps — Green phenolic

Lapping Compound:

Rough Laps — Aluminum oxide 38 to 500 and 38 to 900 grit

Finish Laps — Cerium oxide (1 μ grit).

After an extensive program to determine the settings and materials, it was discovered that an accurate set-up procedure was absolutely mandatory. With the set-up procedure developed and proven, motor speed determined, lap pressure and material solved, and compound mixture standardized, rotor quality (sphericity) still could not be assured. Although spheres could be produced with a sphericity of 0.0508 μm (2 μin.), the required consistency and reliability could not be achieved during each rotor processed. This prompted a redesign of every detail built into the machines being used. With the knowledge gained using this type machine, it was determined that rigid and precisely fitted parts were required. This attention to detail resulted in the first six rotors falling below 0.0254 μm (1 μin.) sphericity; therefore, as many quality rotors as is needed can be produced with this state-of-the-art polishing system.

LAPPING MACHINE STRUCTURE

The original four lap machine was built on 1.27 cm (0.5 in.) raw aluminum plate and proved to be susceptible to vibrations; therefore, a 3.175 × 50.8 × 60.96 cm (1.25 × 20 × 24 in.) tooling plate giving a good solid foundation was used in the new design and is shown in Figure 3. All mounting surfaces were machined flat and key ways were added to precisely locate the component parts. The platform is supported by 3.81 cm diameter × 25.4 cm (1.5 diameter × 10 in.) long solid aluminum rods, mounted with 0.95 cm (0.375 in.) socket head cap screws.

The 20 deg ramp blocks must be spaced exactly 120 deg apart, otherwise the convergence of the shaft centerlines cannot be made precisely under the centerline of the top motor shaft. Using precision machining techniques, key ways were cut (shown in Fig. 3) in the base plate, bottom, and face of the ramp blocks and the motor mounting blocks. Using the setup procedure detailed in the paragraph entitled Lapping Procedure for 3.81 cm (1.5 in.) Diameter Quartz Rotors, the motors can be indicated on to the mounting blocks and the key ways, thus allowing adjustments without losing directional accuracy.

A gaging system (shown in Figs. 4 and 5) has been developed to align the lap motors to within 12.7 μm (500 μin.) Total Indicated Runout (TIR). The system measures height as well as centering.

The lapping compound is dispensed from a 2.5 liter (0.66 gal.) tank that uses a 70 rpm paddle type agitator. A solenoid switch, controlled from the cam box dispenses the compound at 15 sec intervals for a 1 sec duration.

The top lap motor is keyed to a 2.54 × 13.97 × 17.78 cm (1 × 5.5 × 7 in.) angle plate. The plate is permanently fixed to the platform. The key allows for up and down adjustments while maintaining the centerline of the lap perpendicular to the base plate.

It is essential that all four lap motors run within 1 rpm of each other (see lapping instructions for speeds). The motor speed controllers supplied by the manufacturer are sensitive enough to set the speed accurately, but do not provide a rpm indication of the actual speed of the motors; therefore, a digital tachometer is used to set each motor. The speed settings are adjusted by inserting the contact or rubber tip of the digital tachometer into the center drilled hole in the end of the shaft. This method allows all four motors to be adjusted to exactly the same speed.

The manufacturer and model number of the motor controller are listed below:

Minarik Electric Company
Los Angeles, CA 90013
Model No. SL15

Figure 3. Polishing machine base plate.

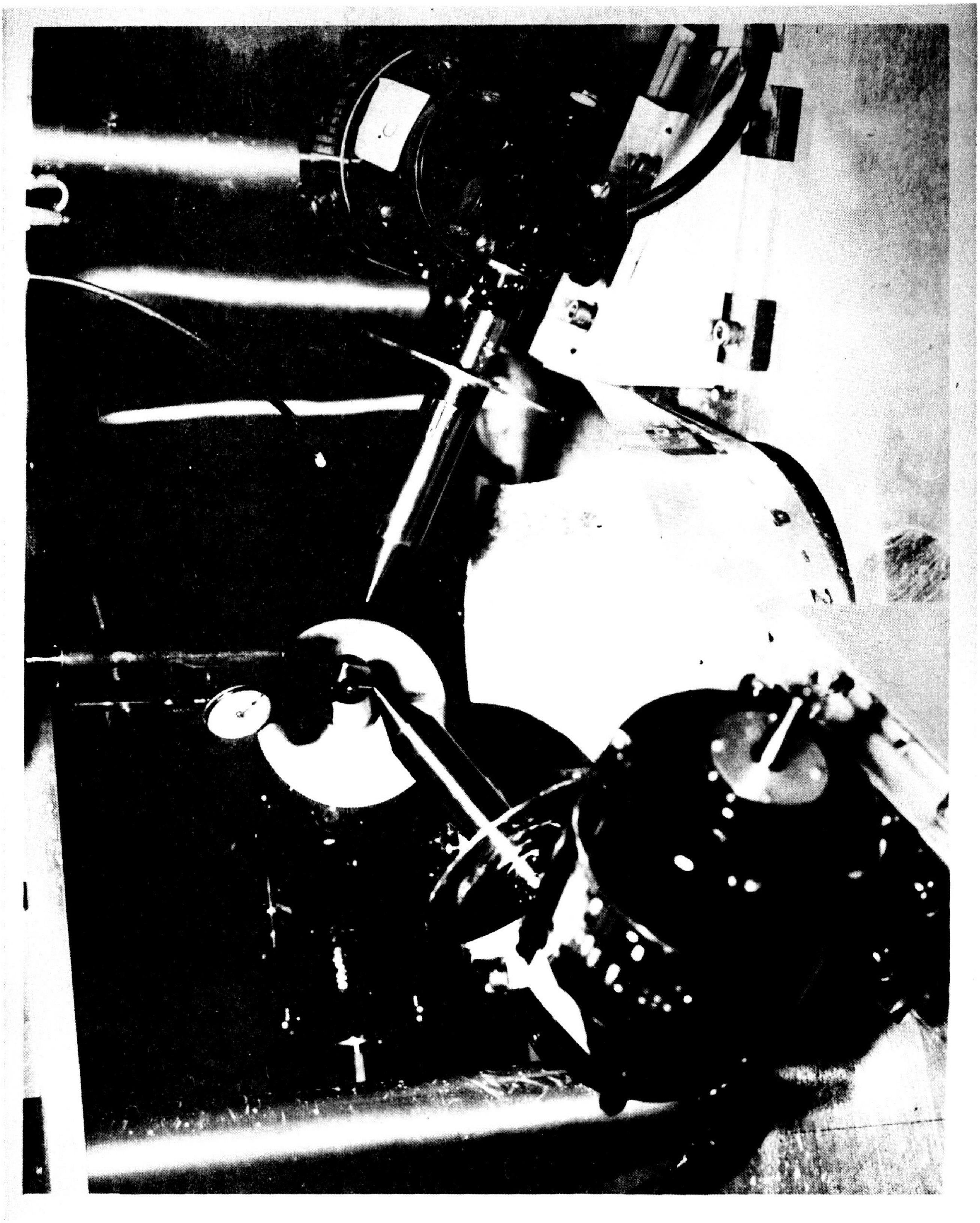

Figure 4. Motor alignment gaging system (view 1).

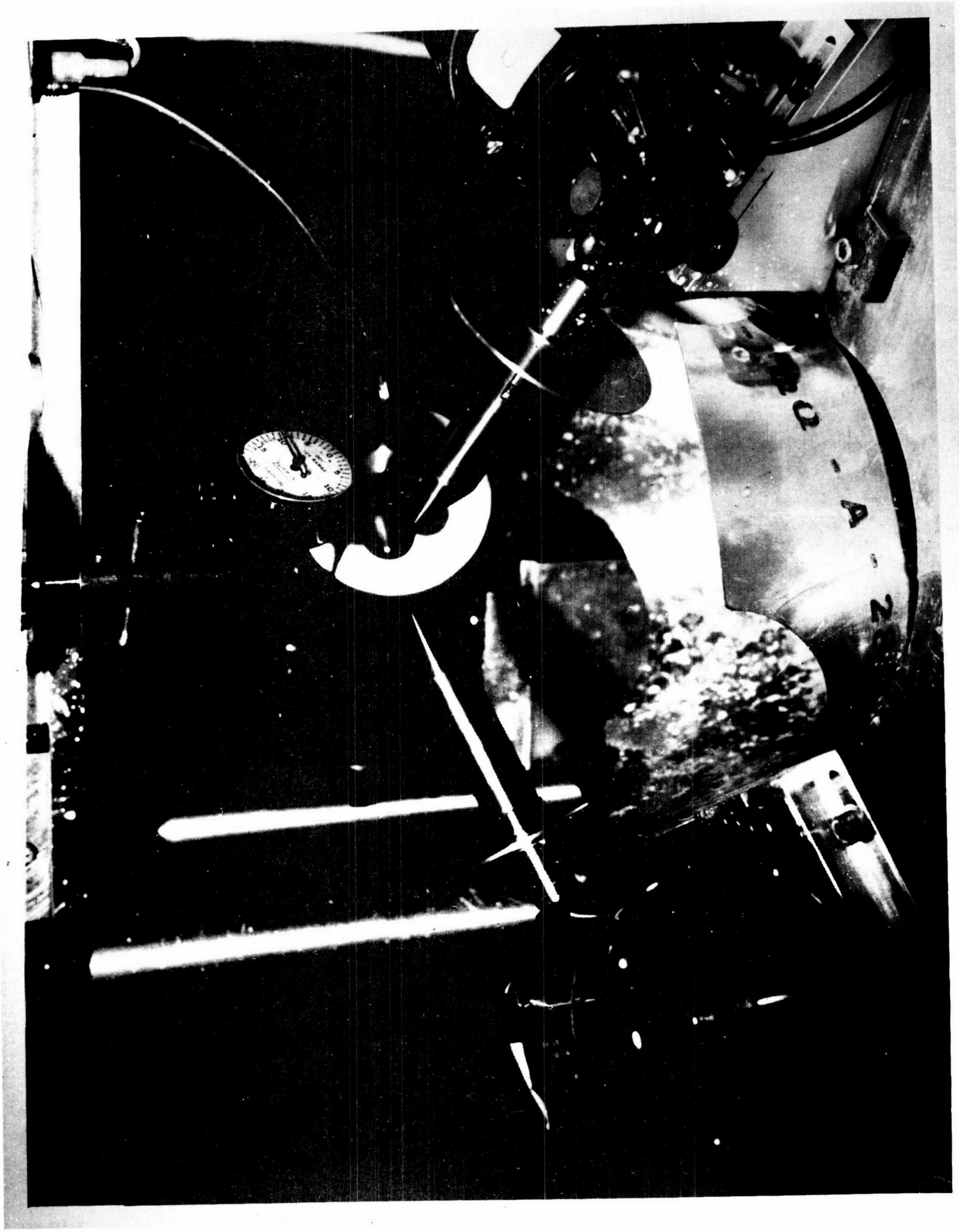

Figure 5. Motor alignment gaging system (view 2).

The manufacturer and model number of the digital tachometer are listed below:

Power Instruments, Inc.
7352 North Lawndale Avenue
Skokie, IL 60076
Tak-ette, Model No. 1707

The motor switching sequences are controlled by cams as discussed in Reference 1. By reversing the motors in the proper order, the rotor is always rotating, i.e., tumbling, thus ensuring sphericity by lapping all of the surface area an equal amount and thereby removing an equal amount of stock.

The finishing machine should be enclosed to prevent dust particles from the air from coming into contact with the spheres and to maintain a semi-controlled environment during the lapping operation. Figure 6 shows the polishing machine in the complete assembled and working state.

Precision alignment of the motors and laps is an absolute requirement to produce quality rotors and is delineated in the section entitled Lapping Procedure for 3.81 cm (1.5 in.) Diameter Quartz Rotors.

ROUGH LAPPING

Rough lapping is a process by which quartz spheres are lapped to within 38.1 μm (1500 μin.) of the desired diameter and to within a 0.254 to 0.381 μm (10 to 15 μin.) sphericity. Quartz spheres 39.4 mm (1.550 in.) diameter are received from the vendor in a rough-out condition. These spheres are rough lapped to the nominal dimensions +38.1 μm (1500 μin.), which is needed for the final finshing. The roughing lap machine (shown in Fig. 7) is identical to the finishing machine except for the automatic compound dispenser. The compound is applied manually from a squeeze bottle. A mixture of 100 milliliter (6.76 fl. oz.) of 500 grit aluminum oxide powder to 400 milliliter (27.05 fl. oz.) water is used for the initial rough lapping process. This mixture gives a stock removal rate of 0.203 to 0.254 mm (0.008 to 0.010 in.) per hour. The same proportioned mixture, but using 900 grit aluminum oxide instead of the 500 grit, should be used for the last 30 minutes. During this rough lapping operation, the operator must measure the stock removal rate a few times and establish a time versus stock removal chart so that run time can be timed by a clock. By timing the run time, the operator can obtain the desired diameter without excessive measurement time.

The original rough laps were made from brass stock and were a holdover from the three lap horizontal machine. During the course of further development, it was determined that laps made from Meehanite (a high grade cast iron) lasted longer, removed stock faster, and produced the best results. In excess of 20 rotors can be rough lapped with Meehanite as opposed to 6 to 8 rotors for brass laps. These laps are shown in Figure 8.

Rough lapped spheres will be round to about 0.3048 to 0.381 μm (12 to 15 μin.). The required step-by-step procedure to produce quality rough lapped spheres is covered later in this report.

Figure 6. Polishing machine with enclosure.

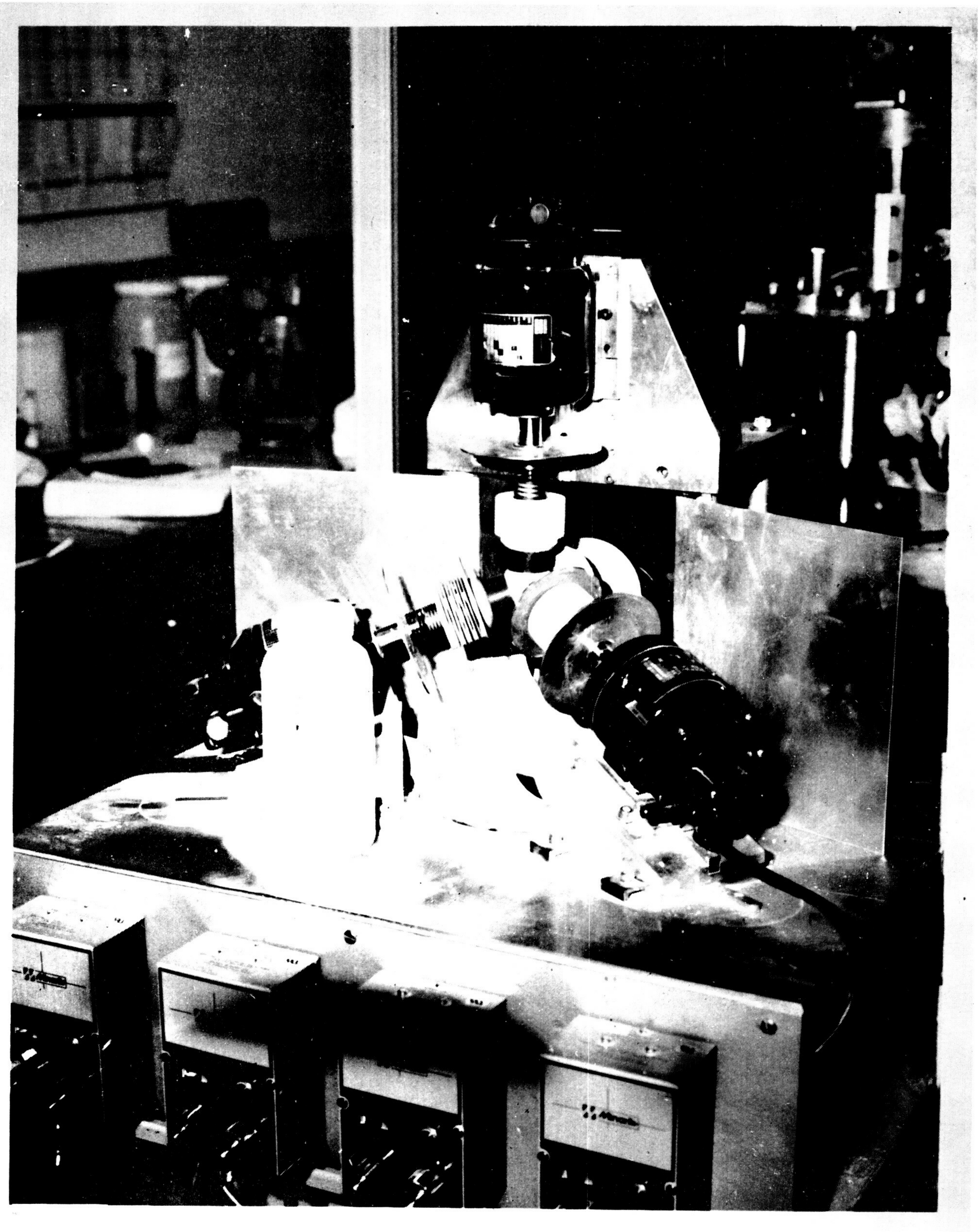

Figure 7. Rough lapping machine.

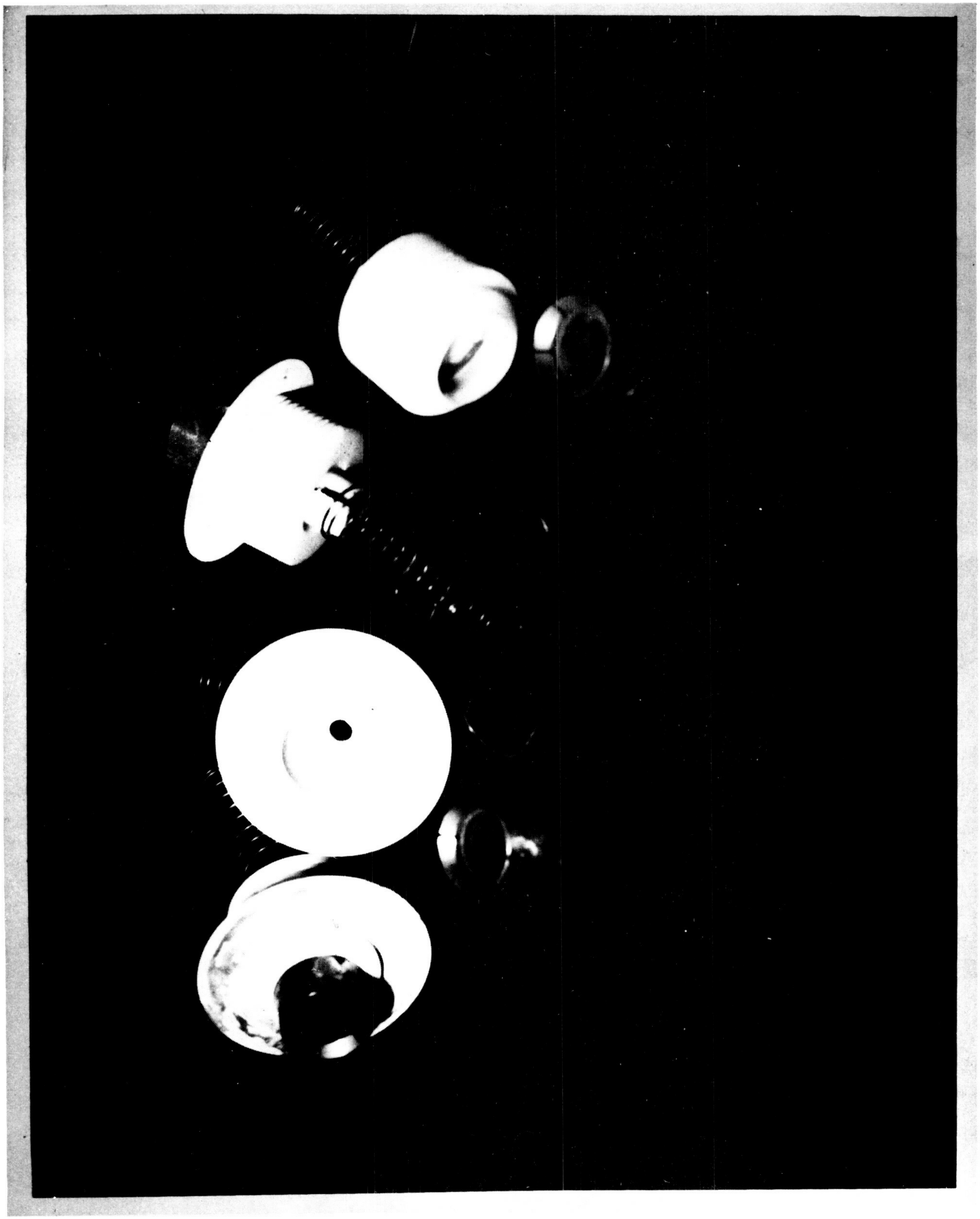

Figure 8. Meehanite laps.

FINISH LAPPING

Throughout this discussion, the words polishing and finish lapping will be used interchangeably. In a traditional optical polishing process, pitch laps are generally accepted as the proper material to use in the production of optical quality finishes. The flowing characteristic of pitch renders it unsuitable for rotor finishing. Pitch laps required a dressing operation and in actuality caused the spheres to go out of round instead of becoming more round as the polishing operation progressed. Efforts to solve this problem resulted in a search for a material that could be cast into the correct size, be machined to the configuration required, remain stable, and produce an optical finish on the sphere.

The stability required in the laps was found in a phenolic powder with a wood flour filler (green phenolic powder from Mark V Laboratory, East Granby, Connecticut). This powder is molded into 38.1 mm (1.5 in.) diameter × 22.225 mm (0.875 in.) long castings using a specimen mounting molder at 149 celsius (300°F) at 24.13 MPa (3500 psi) for 10 min. These blanks are then machined into the laps as seen in Figure 9.

The life of these laps exceeds 500 hr of polishing time. Although the laps are initially machined to the nominal rotor radius prior to beginning the polishing operation, approximately 8 hr of initial run time is required for the laps to seat to the precise contour of the spheres being lapped. Once the laps are seated the stock removal rate for the rotor will be 1.651 to 1.778 μm (65 to 70 μin.) per hour. The polishing compound mixture is 100 milliliter (6.76 fl. oz.) of 1 μ cerium oxide to 1 liter (67.6 fl. oz.) of deionized water by volume. The results obtained using these laps are extraordinary in achieving the three things they are required to give: (1) roundness, (2) dimension, and (3) finish.

FINISH LAP MANUFACTURING TECHNIQUES

The finishing laps are molded from green phenolic powder obtained from Mark V Laboratory, 18 Kripes Road, East Granby, Connecticut 06026.

A Buehler Pneumet press is used to mold the casting from which the rotor laps are machined.

Thirty-five grams (1.23 oz.) of green phenolic powder is poured into the 3.8 cm (1.5 in.) mold, then heated to a temperature of 138 to 150°C (280 to 300°F) under a pressure of 0.69 MPa (100 lb) per square inch line pressure, 27.58 MPa (4000 psi) mold pressure for a period of 12 min, cooled, and removed. This will produce a casting of 2.2 cm (0.875 in.) long × 3.81 cm (1.5 in.) in diameter. Epoxy this to an aluminum holder that measures 2.032 cm (0.800 in.) long × 3.027 cm (1.192 in.) diameter with a 2.06 cm (0.812 in.) diameter hole in the center, then machine to the configuration shown in Figure 10.

An alternate method, consisting of a mold which can be used in any furnace, is described as follows: The mold is a steel cylinder 6.985 cm diameter × 10.16 cm long (2.75 × 4 in.) with a 3.81 cm (1.5 in.) diameter bore. This cylinder is mounted on a 20.32 cm (8 in.) diameter × 2.54

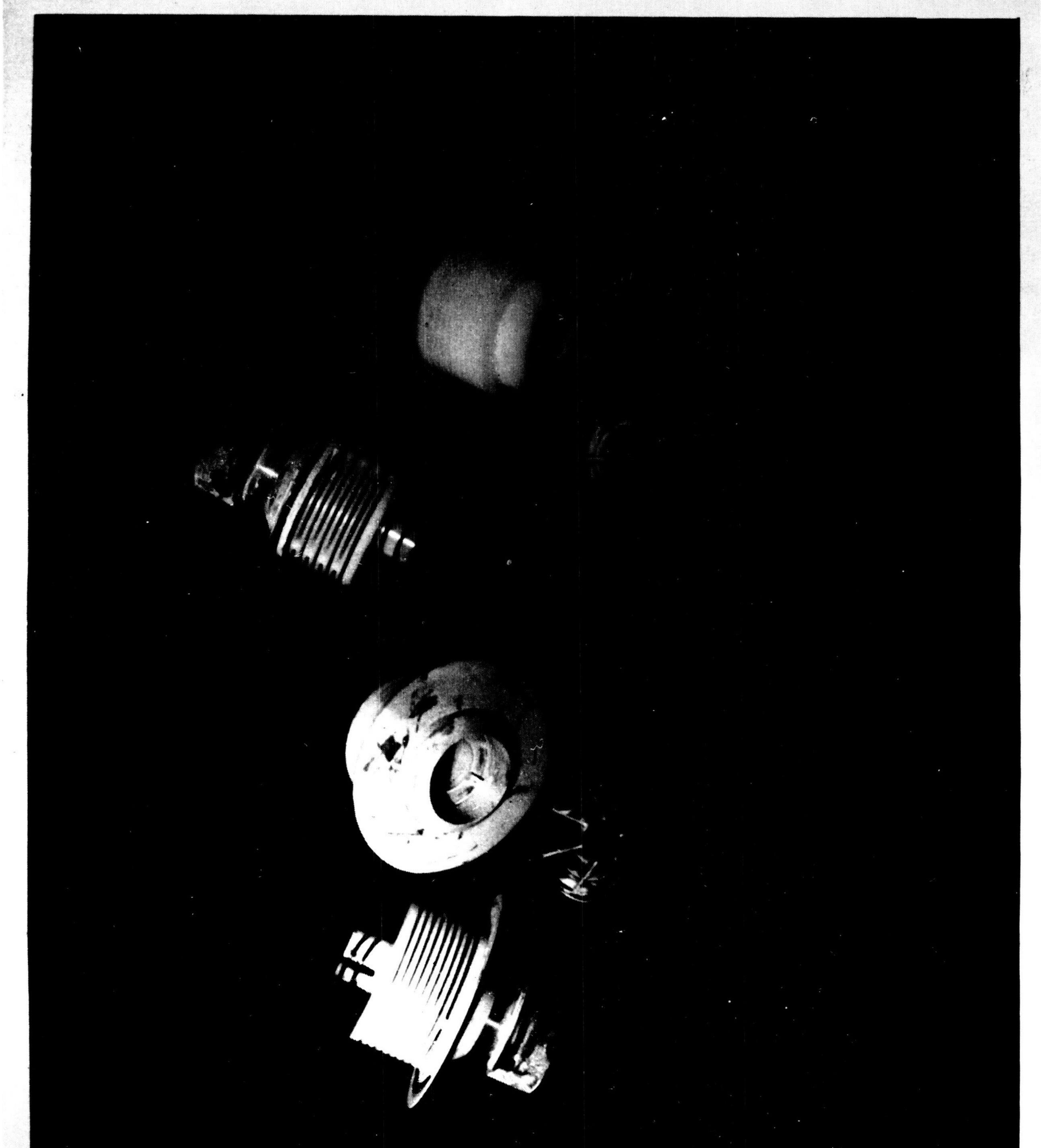

Figure 9. Polishing laps.

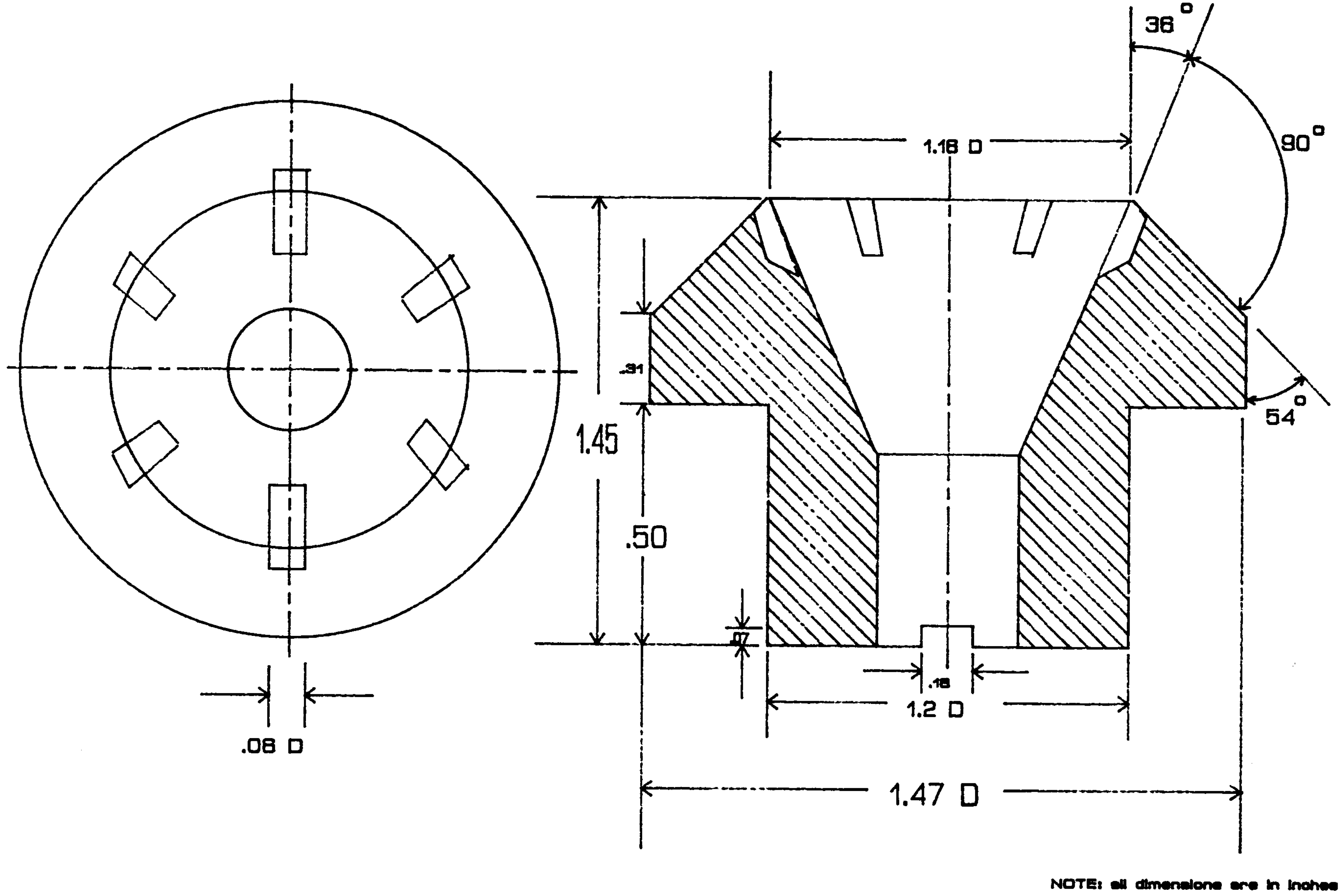

Figure 10. Finishing lap for 3.81 cm (1.5 in.) diameter sphere.

cm (1 in.) thick aluminum plate, drilled and tapped to receive six 1.27 cm (0.5 in.) diameter threaded rods equally spaced around the cylinder. Another plate, the same diameter, with 1.428 cm (0.5625 in.) diameter holes drilled so as to be a free fit over the rods, serves as a pressure plate when molding the powder. A 3.81 cm (1.5 in.) diameter steel plunger 8.89 cm (3.5 in.) long fits under the pressure plate which is loaded by springs. Three 1.71 × 2.86 × 6.98 cm (0.675 × 1.125 × 2.75 in.) and three 1.428 × 2.86 × 6.35 cm (0.5625 × 1.125 × 2.5 in.) High Pressure Low Deflection Die Springs (HPLD) are used to exert pressure on the powder.

Thirty-five grams (1.23 oz.) of powder, heated at 200°C (380°F) for 2 hr makes a blank 3.81 cm (1.5 in.) diameter × 2.286 cm (0.9 in.) long. This blank is then machined to finishing lap specifications as shown in Figure 10.

LAPPING PROCEDURE FOR 3.81 cm (1.5 in.) DIAMETER QUARTZ ROTORS

Step 1. Machine Setup Procedure

The machine setup procedure is applicable to both the rough lapping and finish lapping machines and will not be repeated for each step in the procedure. See the following for machine setup procedures:

1) Mount centering and leveling gages on the spindles of the three base-mounted motors as shown in Figures 4 and 5.

2) Attach dial indicator to the "spindle" of the vertically mounted motor.

3) Rotate top spindle 360 deg, lowering the top motor until contact is made with all three gages. Note the difference in height. Bring all three into the same plane by up or down movement of the firmly secured 20 deg ramp block. Two or three adjustments may be necessary, but the end result should be that all three motor spindles are in the same plane, within 25.4 μm (0.001 in.).

4) Replace dial indicator with fixtured "last word," finger type indicator as shown in Figure 5.

5) Position "last word" indicator so that when it is rotated through 360 deg, the point draws an imaginary 3.81 cm (1.500 in.) diameter circle.

6) Raise or lower top motor so that the ball tip passes through the approximate center of the centering gage tips.

7) Slide ramp blocks in or out until the same indicator reading is seen on all three gage tips. Tighten clamp screws. Swing through again and refine block positions until the difference reading for all three gages is 25.4 μm maximum. This procedure places all three base mounted motors in the same plane,and the rotating axis of the top motor is in their center. Remove the indicator gages and raise the top motor to its limit.

8) Set speed of all four motors to 225 rpm for rough lapping machine and 125 rpm for finishing machine. All motors must run at the same speed, ±1 rpm and must be set with a tachometer. With the motor running, push the cone shaped hard rubber tip of the tachometer into the "center drilled" hole on the motor shaft and adjust each motor to the proper speed.

9) With ramp blocks in the position previously described, it may be necessary to repeat steps (1) through (7) to accommodate longer or shorter laps or to change spring pressure. Otherwise, nothing should be moved, even when loading and unloading the rotor, except to make whatever small adjustments found necessary before beginning each day's run.

10) Motor Replacement — When it becomes necessary to change or replace a motor, proceed as follows:

On Rough Lapping Machine — Indicate the spindle in parallel to the ramp mounting plate in one plane. Turn the motor over 90 deg and indicate the spindle in parallel to, and on center with, the key way.

On Finishing Machine — Indicate the spindle in parallel to the ramp mounting plate in one plane. Turn the motor over 90 deg annd indicate the spindle in parallel to the key way. In this plane, the distance from the center of the key way to the center of the shaft is critical and must be set at 71.1 mm (2.800 in.).

Perform steps (10) through (9) as required to ensure proper adjustments of all motors.

Step 2. Rough Lapping Procedure

Two different grits of aluminum oxide lapping compound are to be used: 38 to 500 and 380 to 900. The suggested mixture is 100 milliliter (6.76 fl. oz.) water. Mix in a "squeeze bottle" and apply manually. Use same mixture for both grits. The operator may want to vary this mixture and may do so at his discretion. Regardless of mixture, it is recommended that the last 0.127 mm (0.005 in.) or so be removed with the 900 grit.

Use 1.143 mm (0.045 in.) wire diameter springs and cast iron (Meehanite) laps. With 500 grit compound, stock removal will be about 0.126 to 0.178 mm (0.005 to 0.007 in.) per hour. Change laps and go to 900 grit compound and lap to finish diameter plus 25.4 to 38.1 μm (0.001 to 0.0015 in.).

At this point the rotor should be round in the neighborhood of 0.254 to 0.381 μm (10 to 15 μin.).

To chart the lapping progress a schedule of time versus stock removal should be established and, once this process is determined, it should be maintained.

Step 3. Finish Lapping

Laps: Disalythalate. Made from green phenolic powder with wood flour filler.

Manufacturer:

Mark V Laboratory, Inc.
P.O. Box 310
East Granby, CT 06026

Springs: 2.22 cm O.D. × 6.35 cm long (0.875 O.D. × 2.5 in. long) wound with closed (flat) ends, 3 each 0.94 cm (0.037 in.) and 1 each 0.8382 mm (0.033 in.) diameter spring wire.

Lapping Compound: 1 micron cerium oxide (CeO2).

Mixture: 100 milliliter (6.76 fl. oz.) cerium oxide to 1 liter (67.6 fl. oz.) of deionized water.

Speed: All 4 motors, 125 rpm.

Stock Removal: 1.65 to 1.778 µm (65 to 70 µin.) per hour.

These laps require about 5 hr run time to seat. When the laps are seated to a particular rotor, they are used until the finishing process is completed. When the rotor is within 2.54 to 3.81 µm (100 to 150 µin.) of the required diameter, more frequent measurements are required.

The top lap motor has up and down locating positions that must be determined by the operator and is adjusted as follows: With a rotor loaded in the laps and the motors running, lower the top lap until the spaces between all four laps look the same, i.e., you see the same amount of rotor between all the laps from every angle. At this point the drive pin in the shaft will be at the approximate center of the slot in the bellows. Once this position has been established, the "stop" can be set and no more adjustments are required.

MEASUREMENT TECHNIQUES

Cleaning Procedure

Prior to measuring the rotor, it must be cleaned. Due to the accuracy of the roundness measurements and the small deviation from a perfect sphere, cleanliness is a major concern. Several solvents, acids, and other methods of cleaning were tried but all methods left a residue that, although it was not visible, showed up in the roundness measurement as an error. Because of the residue, continuous wiping was required to obtain a good trace. Therefore, the following procedure gave the best results and is recommended:

1) Remove all jewelry from hands.

2) Wash hands with soap and water.

3) Place a towel in the bottom of the sink to catch the rotor in case it is accidentally dropped.

4) Put on rubber surgical gloves.

5) Use warm running tap water and liquid dish detergent, wash by hand for several minutes, rinsing, and reapplying detergent.

6) After *all* cerium oxide has been removed, hold the rotor under the warm running water for a few minutes to rinse away the detergent suds.

7) Place the rotor on a nylon holder for further cleaning in deionized (DI) water.

8) Rinse rotor in a clean container in at least two liters of DI water. Rinse by holding the rotor in your hand and turning back and forth to rinse the entire surface. This agitation in DI water should continue for several minutes or until satisfaction of cleanliness is guaranteed.

9) Remove from DI water rinse and blow dry with pressurized canned air or dry nitrogen.

10) Place rotor on roundness measuring machine and make roundness measurements.

Rotor Diameter Measurement

Dimensional measurements are made with a Pratt & Whitney measuring machine, commonly known as a "super mike" and is shown in Figure 11. The machine is set up with "do all" quartz gage blocks. The anvil pressure is 400 grams. Using this pressure and considering the density of the quartz sphere, 1.016 μm (40 μin.) is added to the reading taken from the "supermike" for the amount the sphere is compressed. The machine graduations are read in 0.254 μm (10 μin.) increments, but can be interpreted to read in 0.127 μm (5 μin.).

Rotor Weight Measurements

Spheres are weighed on a "Mettler Semi-Micro Balance," Model B-6 (shown in Fig. 12). This balance reads to 5 digits past the decimal. This instrument has been found to be accurate and very adequate for this measurement.

Roundness (Spherecity) Measurements

Spherecity roundness measurements are made on a Taylor-Hopson Talyrond 73 Talynova shown in Figure 13. This state-of-the-art machine leaves no margin for human error and provides a printout along with charts of the roundness measurements. A magnification of 200,000 seems to give the best results. The spheres are measured for roundness using an octagonal method. When one realizes that a 38.1 mm (1.5 in.) diameter sphere, round to 0.0127 μm (0.5 μin.), expanded to the size of the Earth shows a peak-to-valley distance of only 182.8 cm (6 ft), only then can the accuracy of the spheres and the measuring system be comprehended. Figure 14 shows a finished rotor being measured on the Talynova, and Figure 15 is a typical graph and computer printout of the sphericity.

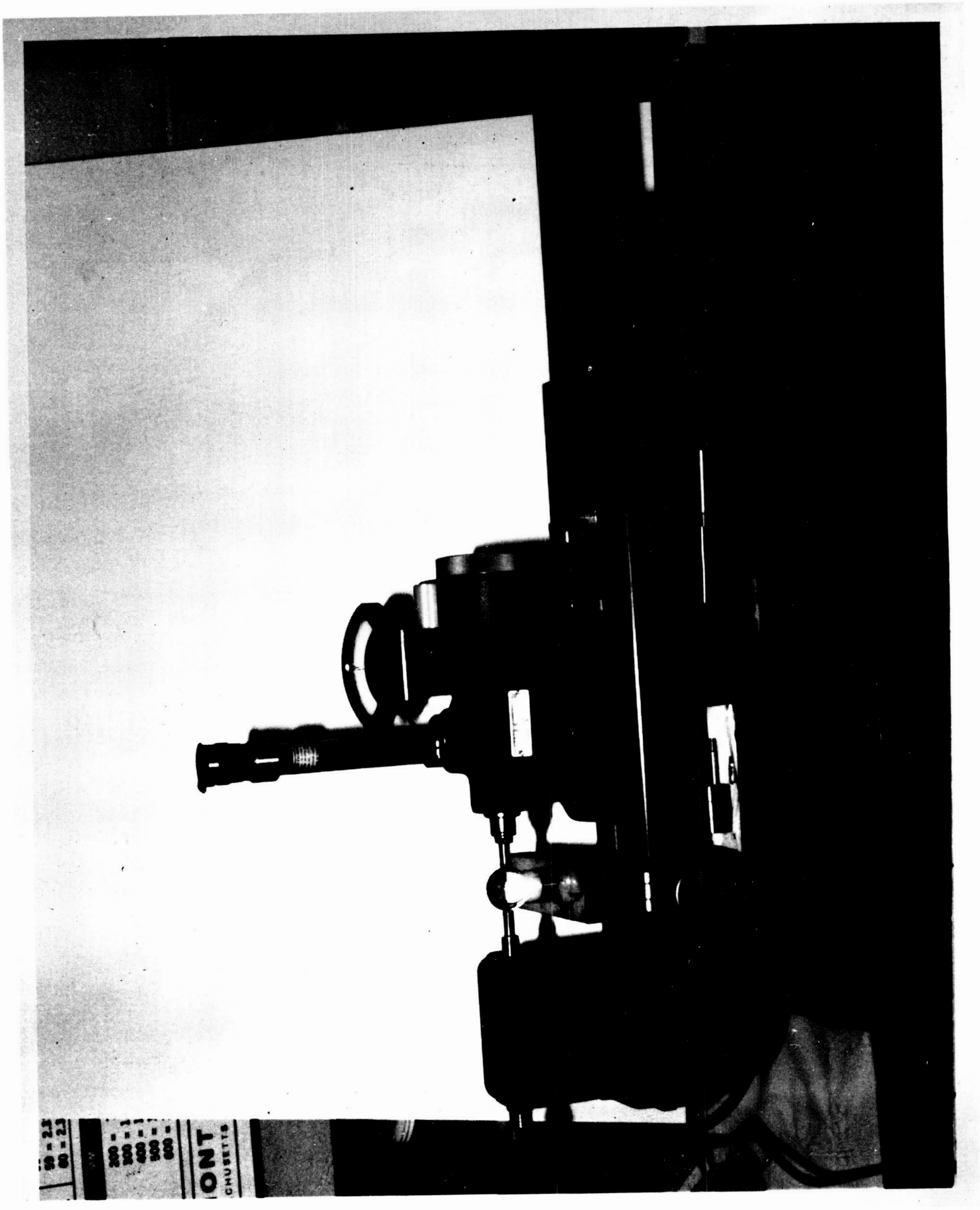

Figure 11. Pratt & Whitney "Super Mike."

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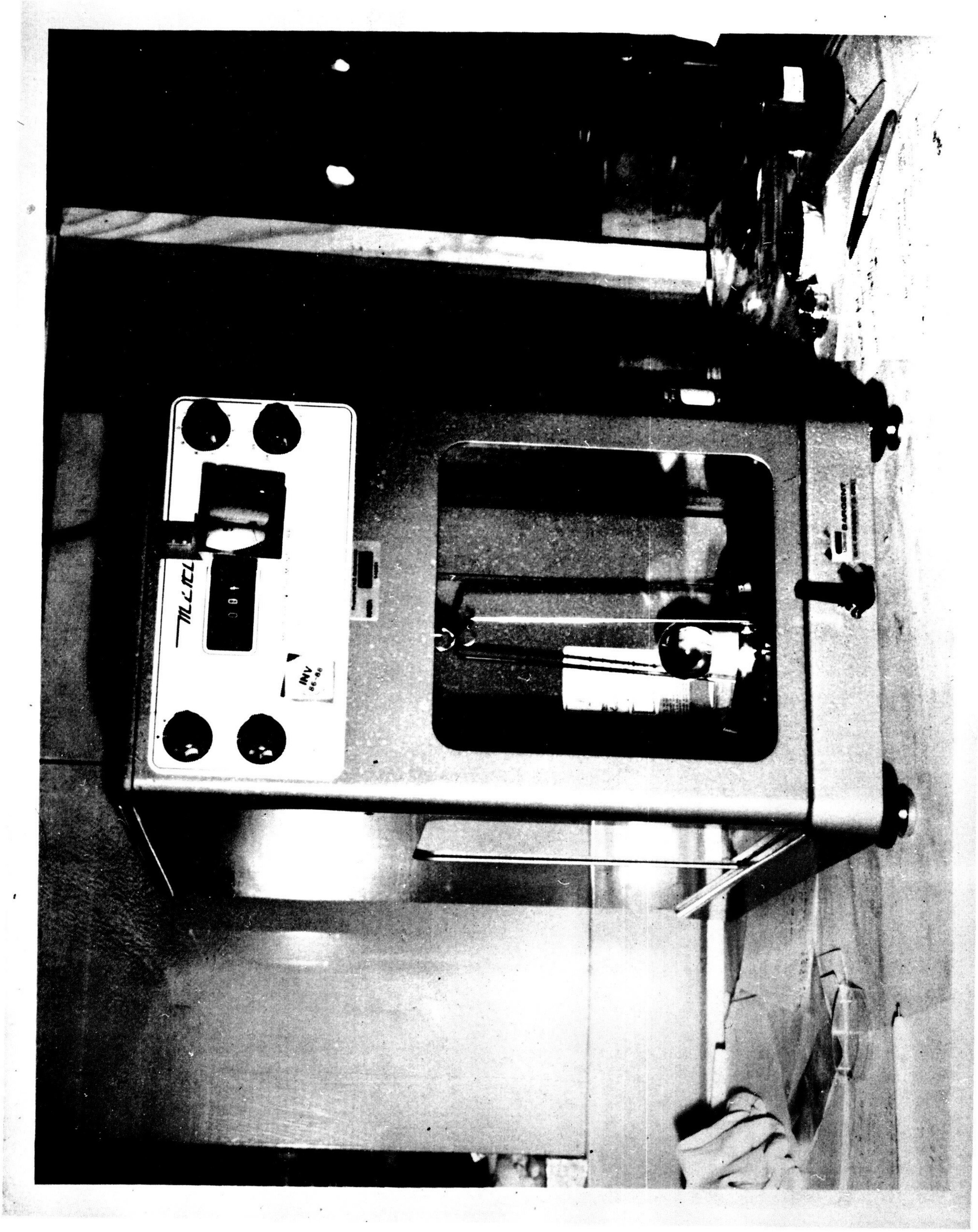

Figure 12. Mettler semi-micro balance.

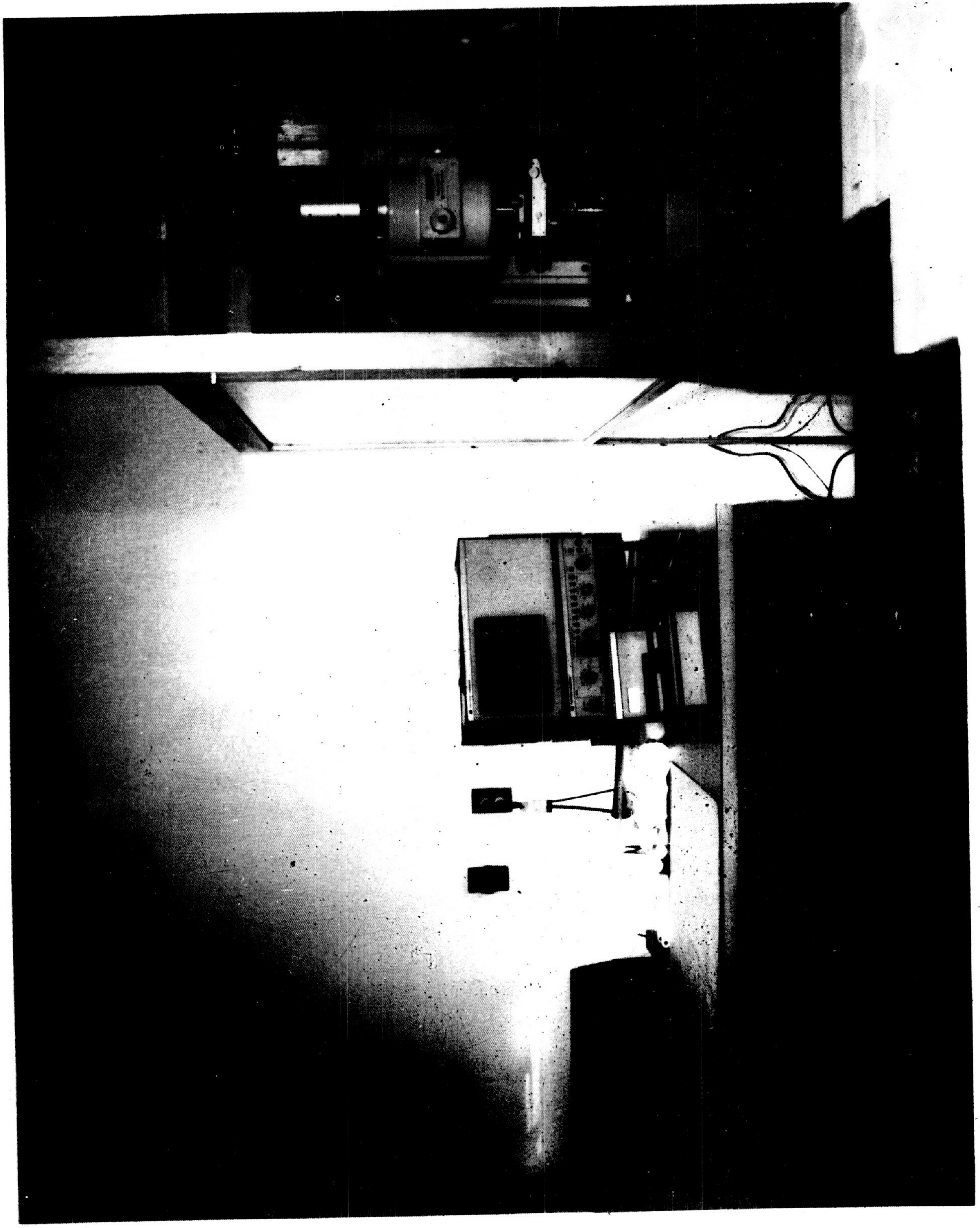

Figure 13. Taylor Hopson, Talyrond, Talynova measurement system.

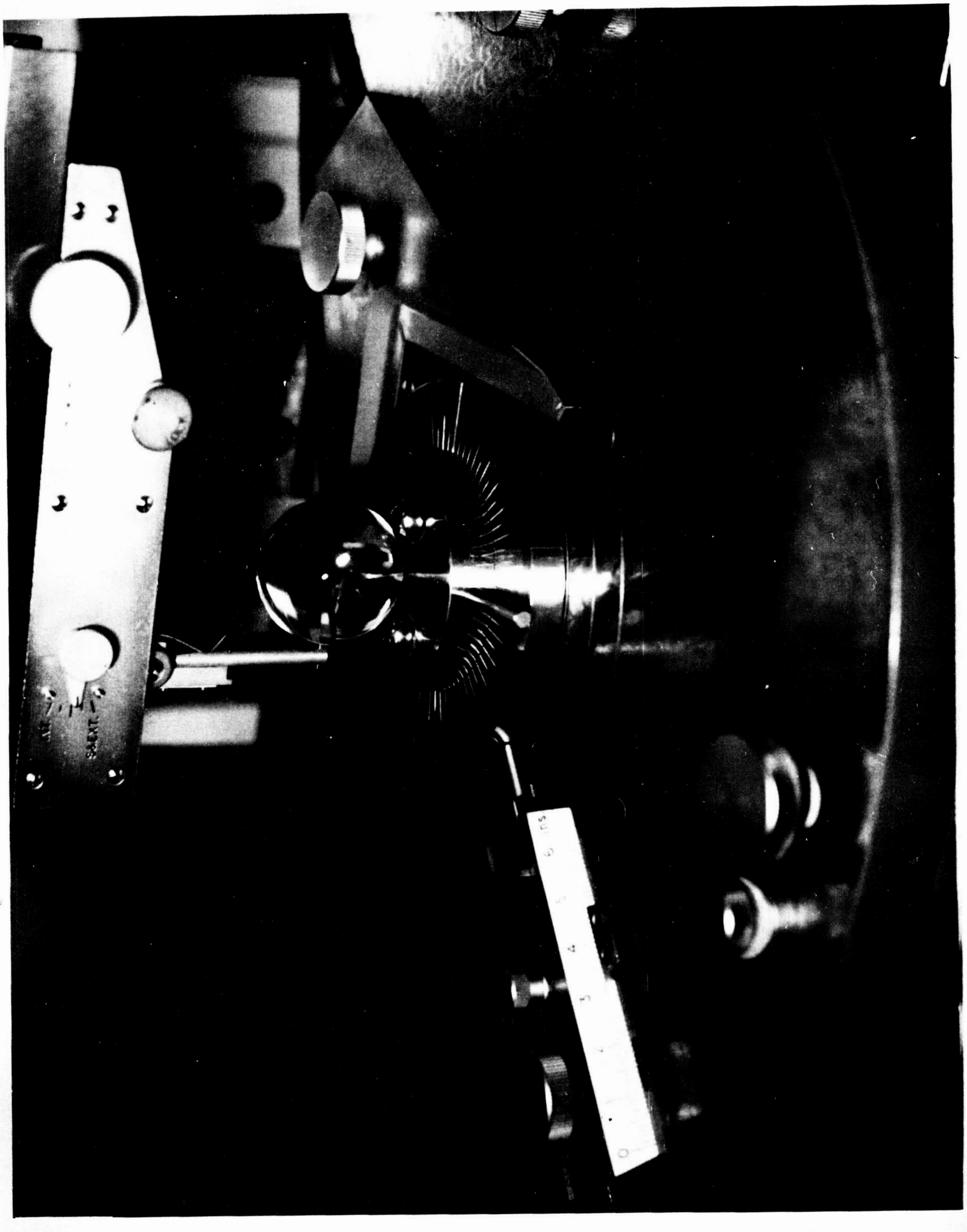

Figure 14. Rotor being measured on Talynova measurement system.

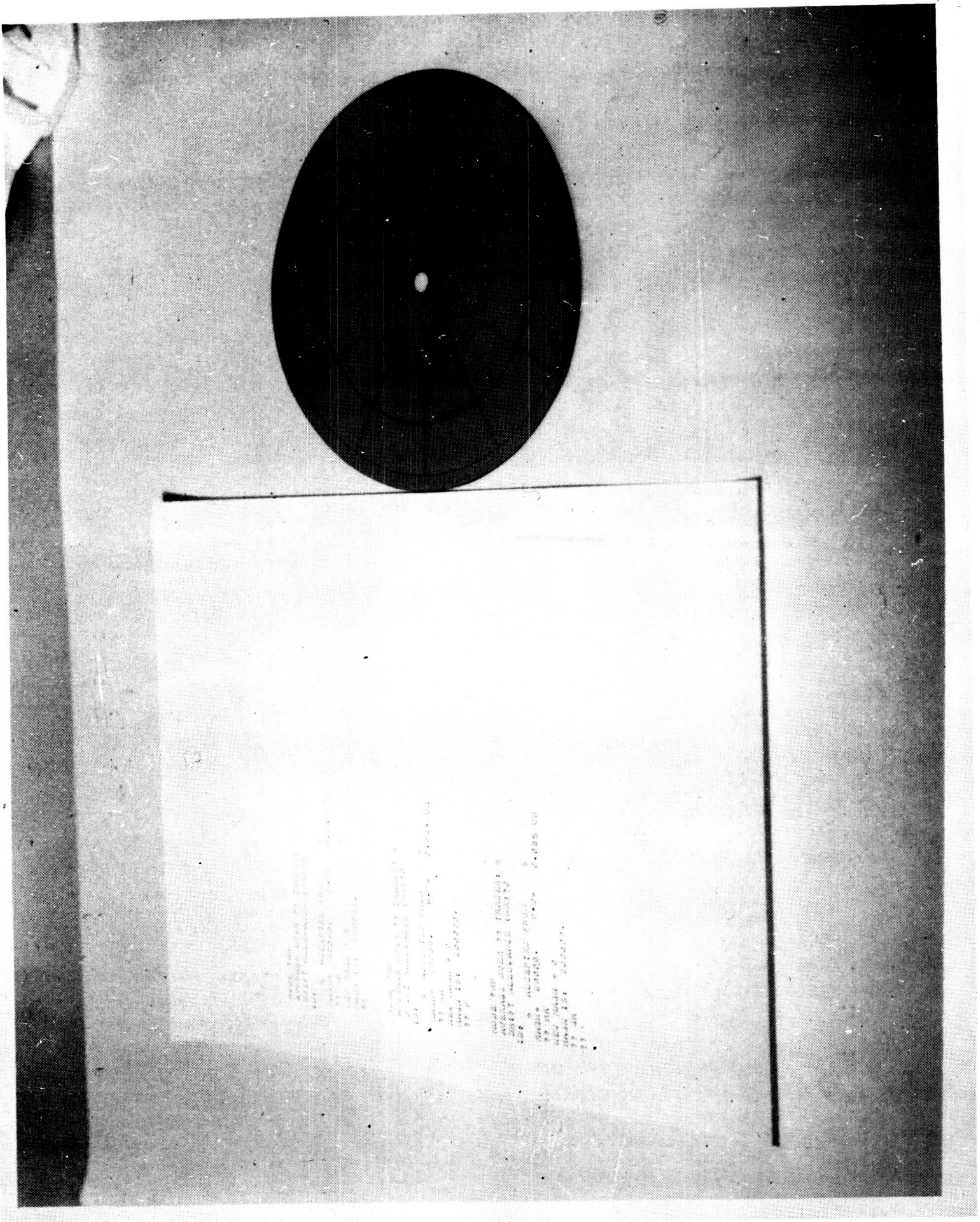

Figure 15. Graph and printout of sphericity measurement.

SUMMARY

The new redesigned lapping/polishing machine (Fig. 6) and the polishing procedure is considered to be a significant improvement in the Gravity Probe B Rotor Development Program. They represent considerable future tangible savings in time and money to the Government. As was stated previously, the first six rotors produced on this machine had a sphericity of less than 0.0254 μm (1 μin.).

Using this new machine and the exact process, rotors can be produced faster and with a sphericity of less than 0.0254 μm (1 μin.) on a consistent reliable basis.

It is concluded, therefore, that this development effort has been very successful and will result in improved gyroscope performance for the Gravity Probe B Project.

REFERENCES

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APPROVAL

1987 PROGRESS REPORT OF MANUFACTURING TECHNIQUES FOR GRAVITY PROBE B GYROSCOPE ROTORS

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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*U.S. GOVERNMENT PRINTING OFFICE: 1987-531-037 Region 4.