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MANUFACTURING TECHNIQUES FOR GYROSCOPES IN GRAVITY PROBE B

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16. ABSTRACT

This is a progress report on the fused silica gyroscope development for Gravitational Probe "B." The design of this particular gyroscope configuration was originated at MSFC and represents a magnitude of improvement in the ease of manufacture over previous models made by MSFC and others. The first gyroscope was made for erection and spin tests only and does not contain the angle readout loops necessary for a functioning experimental gyroscope. The rotor ball described herein is not coated with the ultimate material, niobium, but instead with a sandwich of titanium, copper, and titanium for spin-up test purposes. The coatings and configuration of the flight gyroscope can only be surmised because they are dependent on the results of tests which have not yet been made.

Background, historical information, manufacturing procedures, and sketches for this gyroscope are included to provide a better understanding of the device and the techniques and special tools required to manufacture a fused silica gyroscope to the required specifications.

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BACKGROUND

It is proposed that when Gravitational Probe "B" is launched, it will contain four gyroscopes, two of which are redundant and are for backup. The function of the gyroscopes is to measure the precession rates of a gyroscope in Earth orbit which has been predicted by relativity theory. Since the maximum expected precession will be only seven arc seconds per year, the gyroscope must have a natural precession rate far lower than any known gyroscope that has ever been made.

The concept of the project was originated at Stanford University and their hardware was provided under contract to the Minneapolis Honeywell Company. About four years ago, Marshall Space Flight Center was requested to participate in the project because of the expertise which the Center possessed.

The problems with the gyro at that time were as follows:

1. The rotor balls were too much out of round.

2. Arcing occurred between the rotor ball and the electrodes.

3. The housing was too complex in design and therefore too difficult to manufacture to required tolerances.

The gyroscope described in this report is a test device to prove MSFC's design concept. This first gyroscope will be used to determine the rotor spin velocity and the efficiency of the rotor electrostatic suspension system at ambient and cryogenic temperatures.

INTRODUCTION

Gyroscope No. 1 consists of three main parts, the rotor and two housings. The rotor is a fused silica sphere 38.1 mm (1.5 in.) in diameter. Dimensional tolerance of the rotor for the flight model gyroscope calls for a diameter tolerance of ±2.54 by 10^{-6} mm. This tolerance is undesirably stringent on this gyroscope because the present method of monitoring rotor revolutions per minute is done by monitoring the voltage across the erecting electrodes, which changes in proportion to the eccentricity of the rotor. Too perfect a rotor will show no changes in the feedback voltages but a rotor slightly out of round will. Accordingly, the rotor in this gyroscope is purposely made 330 by 10^{-6} mm out of round. The housings are also made of fused silica and, while the tolerances are not so critical on these parts, they are no less difficult to make. The housings are two hemispherical cavities drilled and machined as shown in Figures 1 and 2. The most difficult tolerance to hold is cavity sphericity which is 635 by 10^{-6} mm.

The two most critical tolerances are the rotor roundness and the cavity sphericity because, if the gap between the rotor ball and the housing is too wide, excessive amounts of helium will leak into the electrode areas resulting in electrical breakdown.

SPECIAL TOOL REQUIREMENTS

The following are special required tools:

1. A roundness measuring machine such as a Talyrond. The accuracy of the spindle in this machine is such that in 95 percent of the tests made of a truly round specimen, the maximum departure of the trace from a true mean circle does not exceed one millionth of an inch (25 by 10^{-6} mm). This machine is not capable of measuring to the accuracy needed in a flight gyroscope.

2. A linear measuring machine such as "Super" micrometer accurate to 10 millionths of an inch (250 by 10^{-6} mm).

3. Gage balls of "Cervit" or fused silica to measure cavity size. These were not available commercially and were made in-house.

4. Balls made of brass and quartz to lap the spherical cavities in the housings.

5. A lapping machine such as a Lapmaster to lap the flat surfaces on the housings.

6. Various special chucks, jigs, and fixtures. These were made in-house to hold the ball and housings during the manufacturing process.

7. A ball-lapping machine such as the one shown in Figure 3. This machine was made in-house with four sewing machine motors as shown. Probably other designs would work as well since getting a truly round ball is mostly a matter of operator skill and is not inherent in the machine.

8. A sputtering machine capable of a 500-W sputtering rate with two 6-in. targets and a 2000-W radiant substrate heater. The substrate table should be capable of adjustment so there can be as much as 5 in. between the table and the targets.

9. A cylindrical grinding machine such as the Brown and Sharpe Model 1020 with a 320-grit standard diamond wheel and a 70° 320-grit diamond wheel.

10. A curve-generating machine such as the Strasbaugh Universal Grinder with various sizes cup diamond cutters.

11. Various hand tools such as hones, optical flats, lathe tools, etc.

12. A jig boring machine with an angle indexing table for drilling the holes in the housing.

13. Diamond drills for drilling the holes in the housing.

SPECIAL SKILL REQUIREMENTS

The quartz used to produce a flight quality gyroscope is extremely expensive. It is therefore mandatory that the machinist who makes the parts have the required skill. The skill is only acquired by many hours of practice with cheaper material and even then the personality of the machinist has a lot to do with the accuracy of the end result. The best gyroscope parts will be made by a man with the personality typically described as a "fuss budget."

PROCESS FOR THE MANUFACTURE OF A FUSED SILICA GYROSCOPE ROTOR

The following steps are necessary to produce a gyroscope rotor to the desired tolerance. Since grinding in a machine produces surface stress in fused silica and since lap stock is needed to make the ball "come" round, the ball is made at least 0.750 mm oversize.

1. It is essential to start with a piece of optical quality fused silica which should be homogeneous as possible. There should be no deviations in the index of refraction across a 50-mm cube greater than 1×10^{-6}. The fused silica should preferably be in the form of a cube at least 45 mm on an edge. A cube is used so that the refractive index can be measured in three axes with a Schlieren type optical test (Fig. 4).

2. Make a suitable fixture to hold the fused silica in a curve generating machine and cement the fused silica to the fixture with a good grade of blocking pitch.

3. Grind the ball from the fused silica cube with a diamond cup cutter in a curve-generating machine to at least 0.762 mm oversize. The result will be a rough ground ball 38.862 mm in diameter. The ball will have to be changed in rotational position several times until the grinding is completed. Figures 4 and 5 show the grinding and polishing sequence.

4. Grind the rough ball down to 0.0508 mm oversize in a ball lapping machine (Fig. 3) using 500-grit aluminum oxide and brass laps. The ball should now be less than 0.00254 mm out of round. This measurement should be made on a Talyrond around several different axes to obtain a good profile of the ball.

If the ball is not sufficiently round, proper care has not been exercised to assure that the brass laps were free enough on the drive shafts or that enough changes in direction were made with the lap drive motors. Before proceeding any further, round up the ball with a ring lap by hand until the ball is less than 0.00254 mm out of round.

5. The last 0.0508 mm of excess stock on the ball must now be polished with pitch laps and Barnsite in a ball-lapping machine such as shown in Figure 3. Before doing this, however, it is necessary to insure that the machine and laps have been thoroughly cleaned of all grit and dirt that might scratch the fused

silica. Particular attention must be paid to good housekeeping. As the last material is polished from the ball, frequent measurements must be made with a super micrometer and a Talyrond to determine the dimensions and be able to gage the rate of stock removal (Fig. 4 and 6).

If sufficient care is exercised, a ball can be produced to within 0.0000254 mm of size with no detectable deviations from roundness. Again, practice and care are the secret.

In Figure 4, it appears that both rotor balls are coated. If the second ball from the left is viewed closely, however, it can be seen that the ball is clear and that the apparent coat of metal is a reflection of the coated ball next to it. When a highly polished piece of fused silica is photographed, it reflects all kinds of images and it is virtually impossible to get an image-free photograph of it.

THE MANUFACTURE OF A GYROSCOPE HOUSING

The terms used to describe the housings are located and defined in Figures 1 and 2. The housings are not exactly alike. The dowel pin, mounting, and spin up holes are rotated 180° in a mating housing. The following steps are deemed necessary to produce a fused silica gyro housing to tolerance:

1. Obtain optical quality fused silica stock and grind it into a cylinder 63.881 mm in diameter. The length required is dictated by the number of housings desired. Use a 320-grit diamond grinding wheel (Fig. 7).

2. Manufacture a pot chuck to hold the 63.881-mm fused silica stock for further grinding. Center the pot chuck in the grinder headstock to better than 0.0254 mm.

3. Saw the stock into 38-mm lengths and mount in the pot chuck. Grind the outside configuration to specification. It will now be necessary to manufacture another pot chuck to hold the housing in order to face off the largest flat side. Leave enough lap stock on this face so that the half holes for the spin up grooves can be drilled as full holes and then lapped to half holes or grooves.

4. Drill all holes, except the dowel pin holes, with diamond drills deep enough that the holes will be completely through when the interior grinding is completed.

5. Lap the mating face of the housing to within 0.0381 mm of finished thickness.

6. Manufacture a pot chuck to hold the housing in a curve generator and grind the spherical cavity almost to drawing dimensions by leaving 0.508 mm of lap stock.

7. Manufacture at least two brass spheres and one fused silica sphere for cavity laps. The brass laps are cut oversize in a lathe, then ground to desired size in a lapping machine (Fig. 3) using 500-grit aluminum oxide abrasive. The brass ball laps should be sized to lap the cavity within 0.0254 mm of the final size keeping in mind that as the laps are used, the cavity gets smaller and deeper and the ball gets smaller. The numbers and sizes of laps required will be determined by the "as ground" size of the cavity and the rate of stock removal from the balls and the the cavity. Extreme care must be exercised during the grinding and lapping operations to prevent chipping the edges of the fused silica. A slight chamfer on the sharp edges will help prevent chipping but as the lapping proceeds, the chamfer will disappear and will have to be redone as required. Frequent measurements should also be taken to keep track of the diameter, the rate of stock removal, and the sphericity. Since the diameter difference of the cavity and the rotor ball is only 7620×10^{-6} mm, great care must be exercised to insure that the cavity is kept spherical within the tolerance on the drawing.

8. Spot face the electrode areas and cut the exhaust groove around the electrodes with a brass lap in a jig boring machine. Exercise extreme caution to prevent tool chatter or the housing will be cracked.

9. Lap the electrodes to depth. They should lie on the surface of a sphere 0.0508 mm larger than the housing radius and should be the same depth. This dimension can be measured with a Talyrond. Because a mirror finish is required the final lapping compound should be Barnsite. The rolled edges of the electrodes must be done with a hand hone and are important to prevent arcing when the gyroscope rotor is erected in tests and in service (Fig. 8).

10. Cut the spin up groove to size with a rotary diamond cutter in a jig borer.

11. Finish lapping the mating face of the housing.

12. Lap the inside cavity to the specified depth and size with a quartz ball lap and 1000 grit aluminum oxide (Fig. 9).

PLATING THE ROTOR BALL

The flight gyroscope requires a rotor ball with a primary coat of niobium but, since this coating process has not been worked out satisfactorily, the rotor for this first gyroscope was coated with a layer of titanium 2500 Å thick, a layer of copper 10 000 Å thick, and a final layer of titanium 2500 Å thick.

The layers of titanium and copper were applied by the process of sputtering. In order to have the metal adhere to the highly polished ball, the following procedure must be used. Since the ball cannot be cleaned by sputter etching due to problems of sphericity and support during sputtering, chemical methods must be used.

Cleaning Procedure

Cleaning should be done as follows:

1. Place the spherical rotor in an organic solvent such as Xylene, and ultrasonically clean for 5 min.

2. Ultrasonically clean in acetone for 5 min.

3. Ultrasonically clean in absolute alcohol for 5 min.

4. Ultrasonically clean in a 25 percent solution of a detergent, such as Aquet, for 10 min.

5. Rinse for 15 min in running, demineralized, deionized water.

6. Ultrasonically clean in a sulphuric acid base glass cleaner for 10 min.

7. Rinse for 30 min in running, demineralized, deionized water.

8. Rinse in distilled water.

9. Rinse in doubly distilled water.

10. Dry with dry nitrogen boiloff gas from liquid nitrogen.

The cleaning should be done in a 10-K clean room and the dried ball should be immediately placed in the sputtering system and evacuated to a pressure no higher than 5×10^{-7} torr as quickly as possible to prevent picking up dust particles on the ball. The ball should then be held at this low pressure for at least 16 h and then heated to approximately 200°C for 30 min. This should drive off the residual water left on the ball except for a monolayer which is tightly bonded to the silica but will cause no problems.

The vacuum seal should not be broken during the sputtering process or afterward until the ball has reached room temperature. This means that a rotating mechanism must be employed to turn the ball to sputter an even coat of metal. This mechanism (Fig. 10) walks the ball around 360° in 25 steps. The tripod pedestal on which the ball rests was lapped on the support surfaces to fit the ball to minimize the current density on the surface of the ball. The coating procedure is to sputter for 1 min, turn the ball one step, sputter for another minute and continue in this manner until the ball had been rotated 360°. At a 100 Å per minute sputtering rate, this puts 2500 Å of titanium on the ball. The sputtering machine used sputters at this rate when set at 400 W output when the distance between the top of the ball and the dark space is 1/4 in.

The copper coat will sputter faster, and the ball will acquire 10 000 Å of copper in 18 min of sputtering time with the same time intervals but a different stepping procedure. The copper is applied with 12 double steps and 6 quadruple steps. The remaining titanium is applied in the same way as the first layer.

The coating process should start immediately after baking and should not stop until all the metal has been applied. The ball is then left in the vacuum chamber for 8 h to insure that it is at room temperature before exposure to the atmosphere.

The ball coating passes the tape peel test and will stand ultrasonic cleaning.

PLATING THE HOUSING ELECTRODES

The electrodes are coated with a layer of titanium 2000 Å thick, a layer of copper 25 000 Å thick and a top coat of titanium 2000 Å thick. The cleaning procedure is the same as for the rotor ball. A fixture must be made (Fig. 11) so that the housing can be indexed to the three 120° positions and held at the proper angle so that the electrode being sputtered is parallel to the target. It is indexed by a bicycle speedometer cable turned by a mechanical feedthrough into the vacuum chamber. The top of the fixture should be positioned precisely at the edge of the dark space.

A plating mask (Fig. 12) must be made to shield the surfaces of the housing from the sputtering where metal is not to be deposited. With the mask in place only the electrodes are exposed.

The sputtering technique is the same as for the rotor ball except that the sputtering times are different.

GYRO ASSEMBLY

Before the spin up groove is ground in the housings, a fused silica ball that exactly fits the housings is inserted into one housing and the other housing is mated with the first. The spin up grooves are then aligned and pins which fit them are inserted all the way into the ball. The exact size ball has been drilled through previously so that a bolt can now be run through the gyroscope to hold the housings in place. The dowel pin holes are now drilled, lapped, and fitted with fused silica pins.

At final assembly, the gyroscope parts are ultrasonically cleaned thoroughly and assembled using the three fused silica pins to align the two housings concentrically. If the dowel pins and dowel holes have been properly lapped, the concentricity will be better than 254×10^{-6} mm (10×10^{-6} in.).

The gyroscope is then mounted to the test fixture with three titanium screws and springs to the test fixture using the mounting holes. The completed assembly is shown in Figures 13 and 14.

PERTINENT DATA ON TEST GYROSCOPE NO. 1

The gap between the rotor ball and the housings is 4114.8×10^{-6} mm (163×10^{-6} in.). The plating on the electrodes in the housings is depicted in Figure 9.

The capacitance across the electrodes was measured to confirm the concentricity and know the electrical load into which the ball support electronics must work. For the following capacitance readings X_1 is the electrode between the intake and exhaust ports for the spin up groove and X_2 is opposite in the other housing. Proceeding around the gyroscope counter-clockwise from X_1 is Y_1 and Z_1. The measurements are with the named electrode in the up position.

X_1	30.05 pf	X_2	30.93 pf
Y_1	31.72 pf	Y_2	31.73 pf
Z_1	31.07 pf	Z_2	31.81 pf

The final rotor ball diameter was 38.109652 mm (1.500380 in.).

CONCLUSIONS

Although the dimensions of this test gyroscope do not meet the tolerances of a flight model, they compare favorably. The two most critical dimensions are the rotor ball roundness and the gap between the spin up groove and the rotor ball. The rotor ball on this first test gyroscope is purposely out of round by 330×10^{-6} mm. The spin up gap is designed to be 3810×10^{-6} mm and it actually is 4114×10^{-6} mm leaving a difference of 304×10^{-6} mm which is very usable for suspension and spin tests (Fig. 15).

The manufacture of Test Gyroscope No. 1 has required the manufacture of fixtures, and the acquisition of techniques and new skills to complete the device. As a consequence, Test Gyroscope No. 2 should not be as difficult to make and should take much less time to finish.

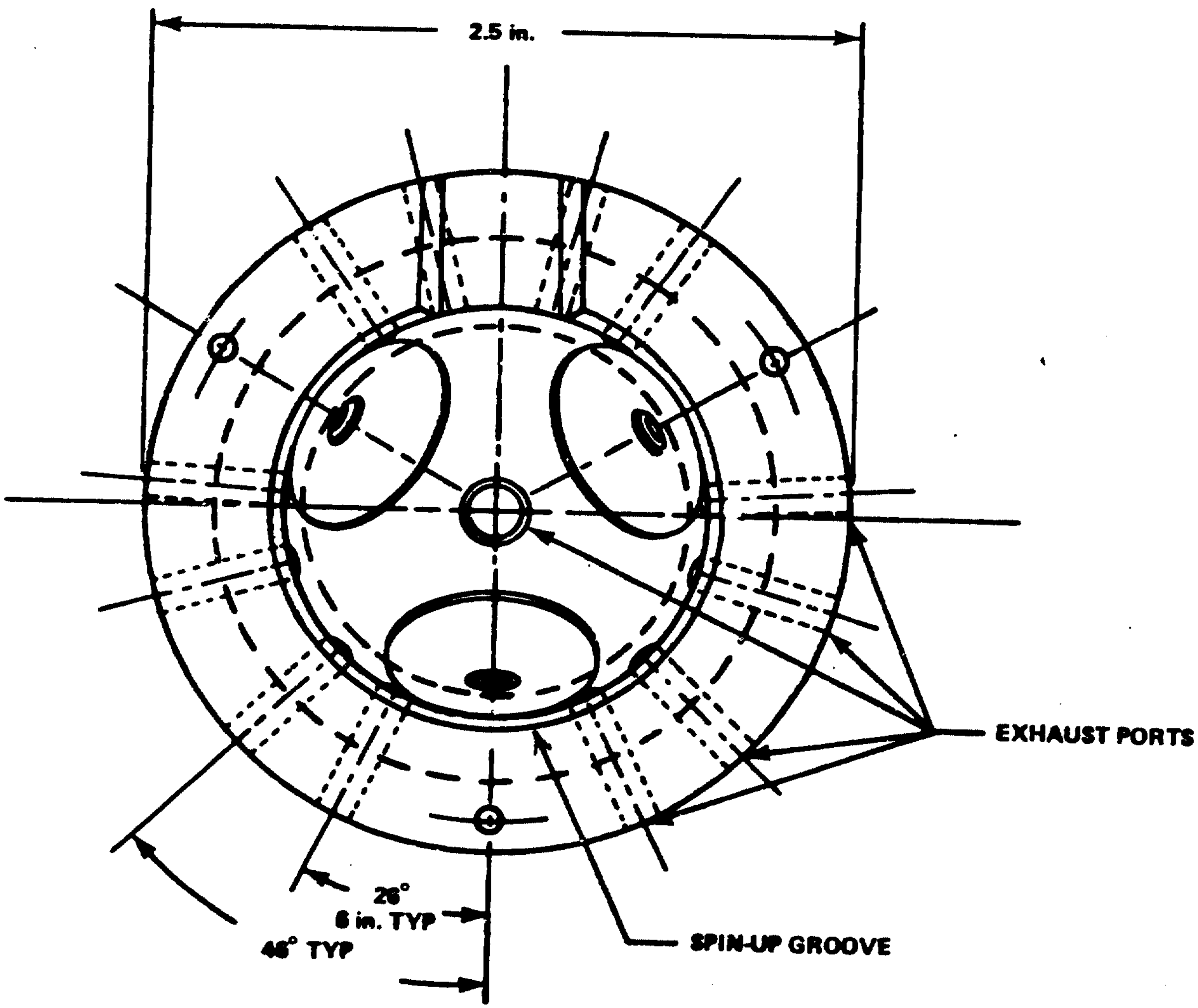

Figure 1. Redesign of relativity gyro.

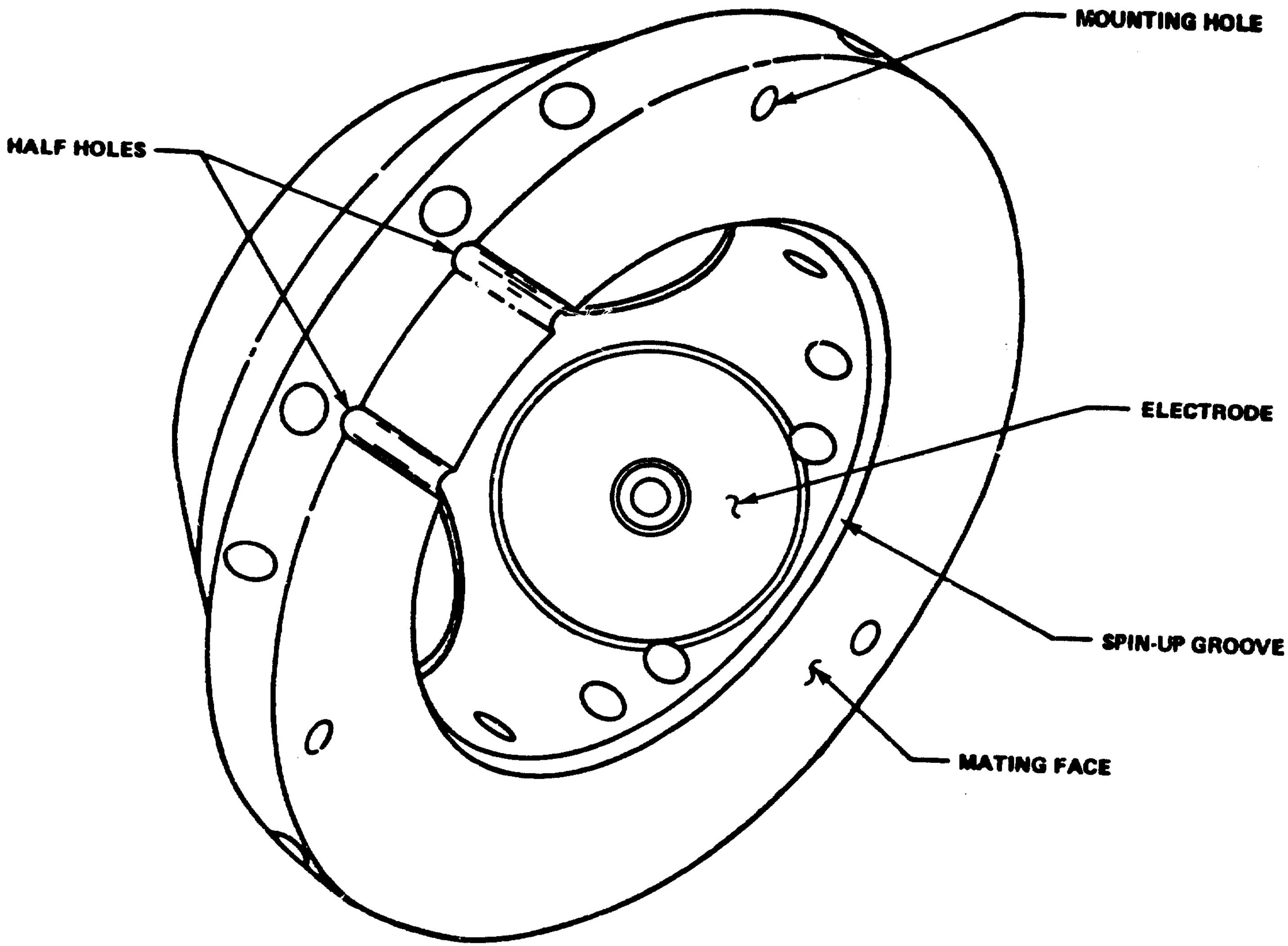

Figure 2. Redesign of relativity gyro.

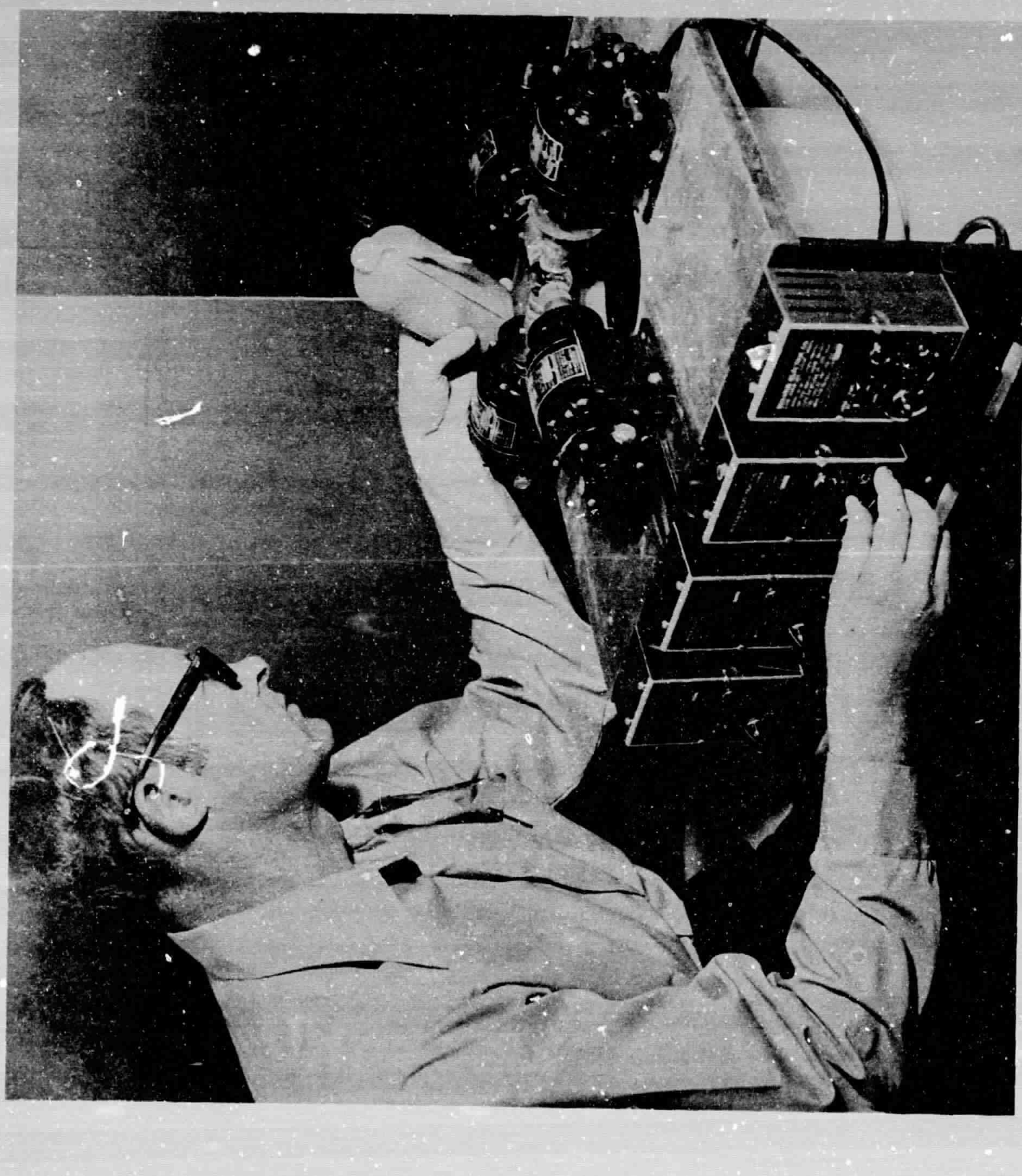

Figure 3. Ball grinding and lapping machine.

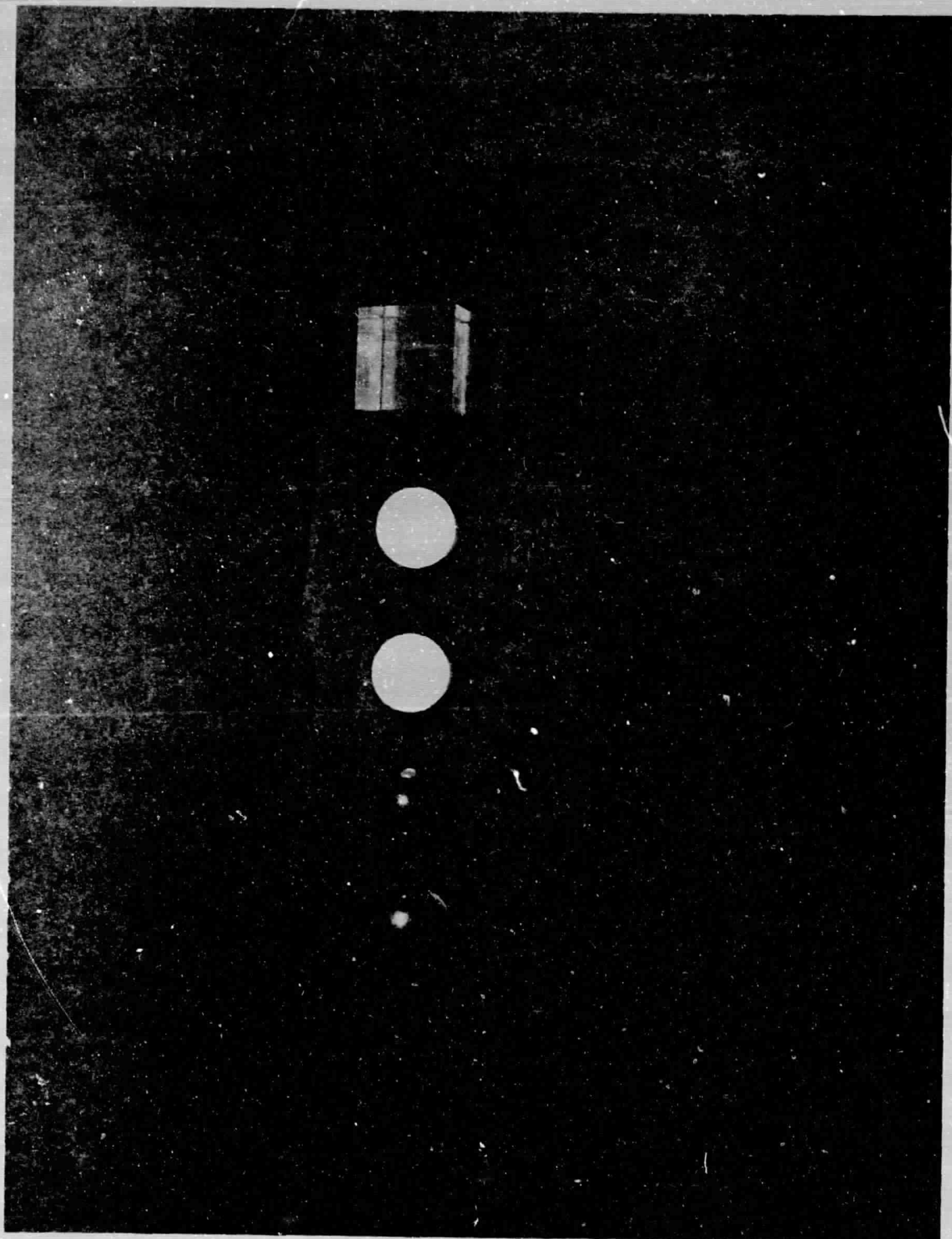

Figure 4. Standard relativity gyro.

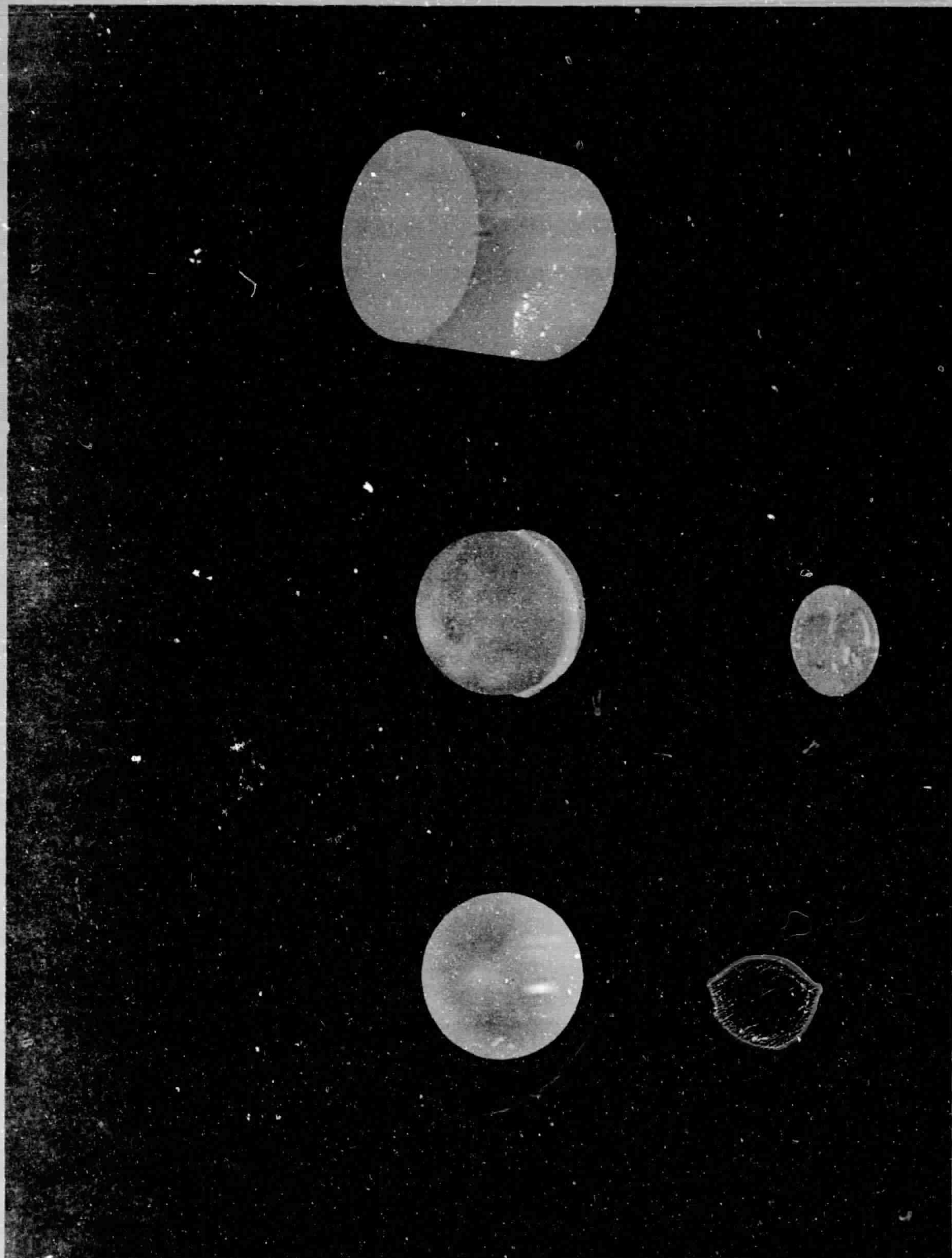

Figure 5. Quartz plate with rough $1\frac{1}{2}$ balls before finishing.

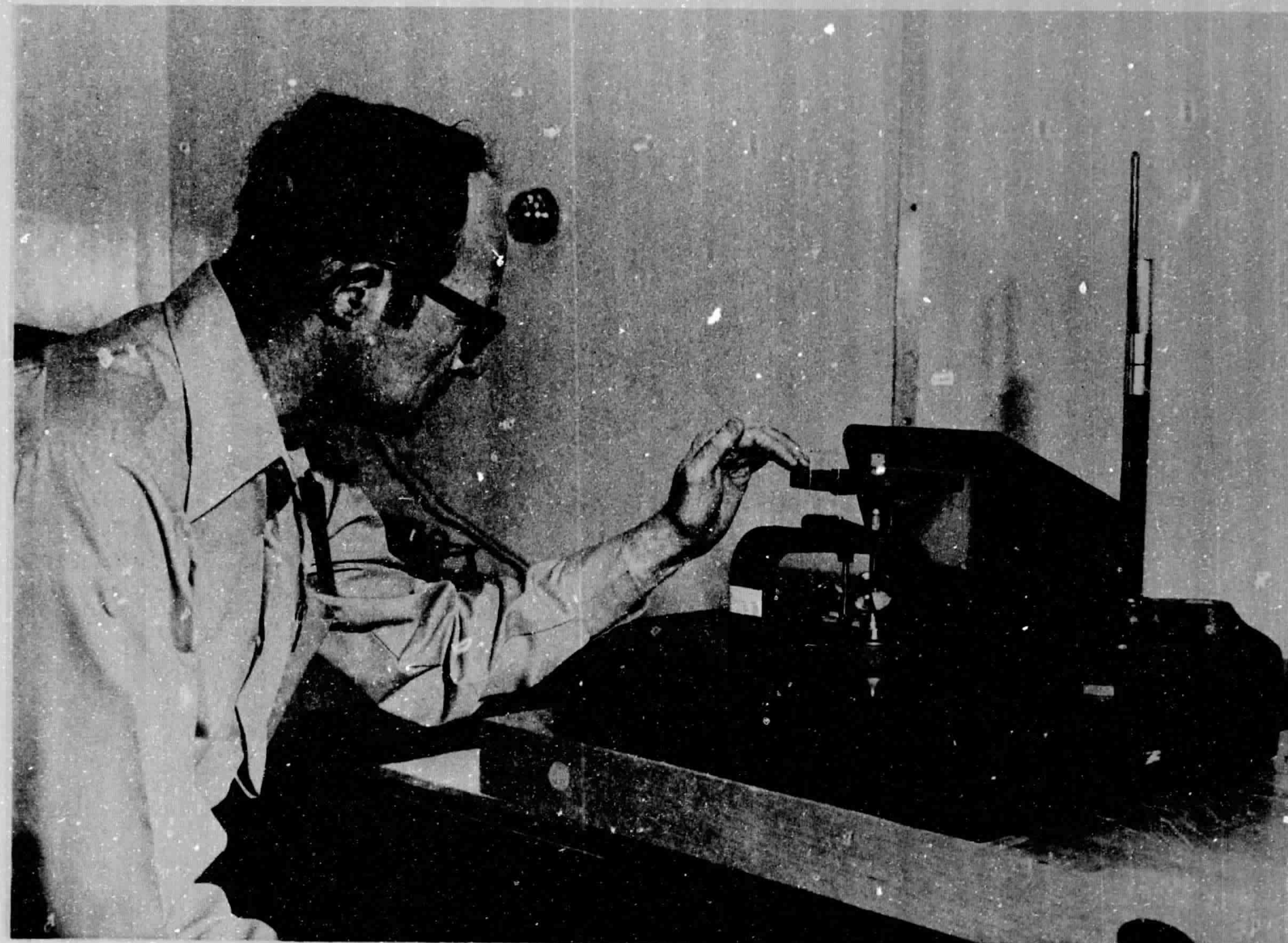

Figure 6. Lightwave micrometer.

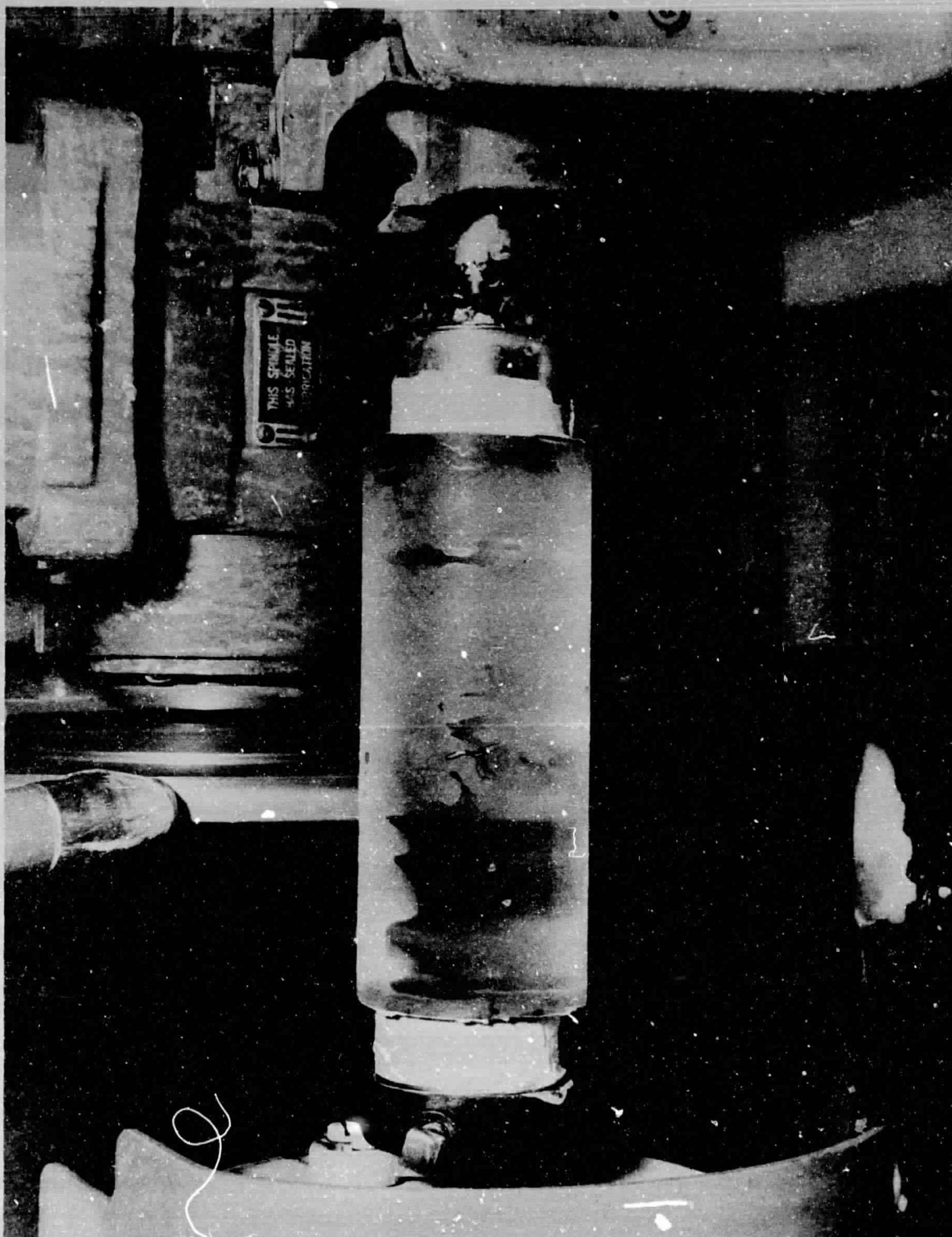

Figure 7. Grinding quartz to size for relativity gyro.

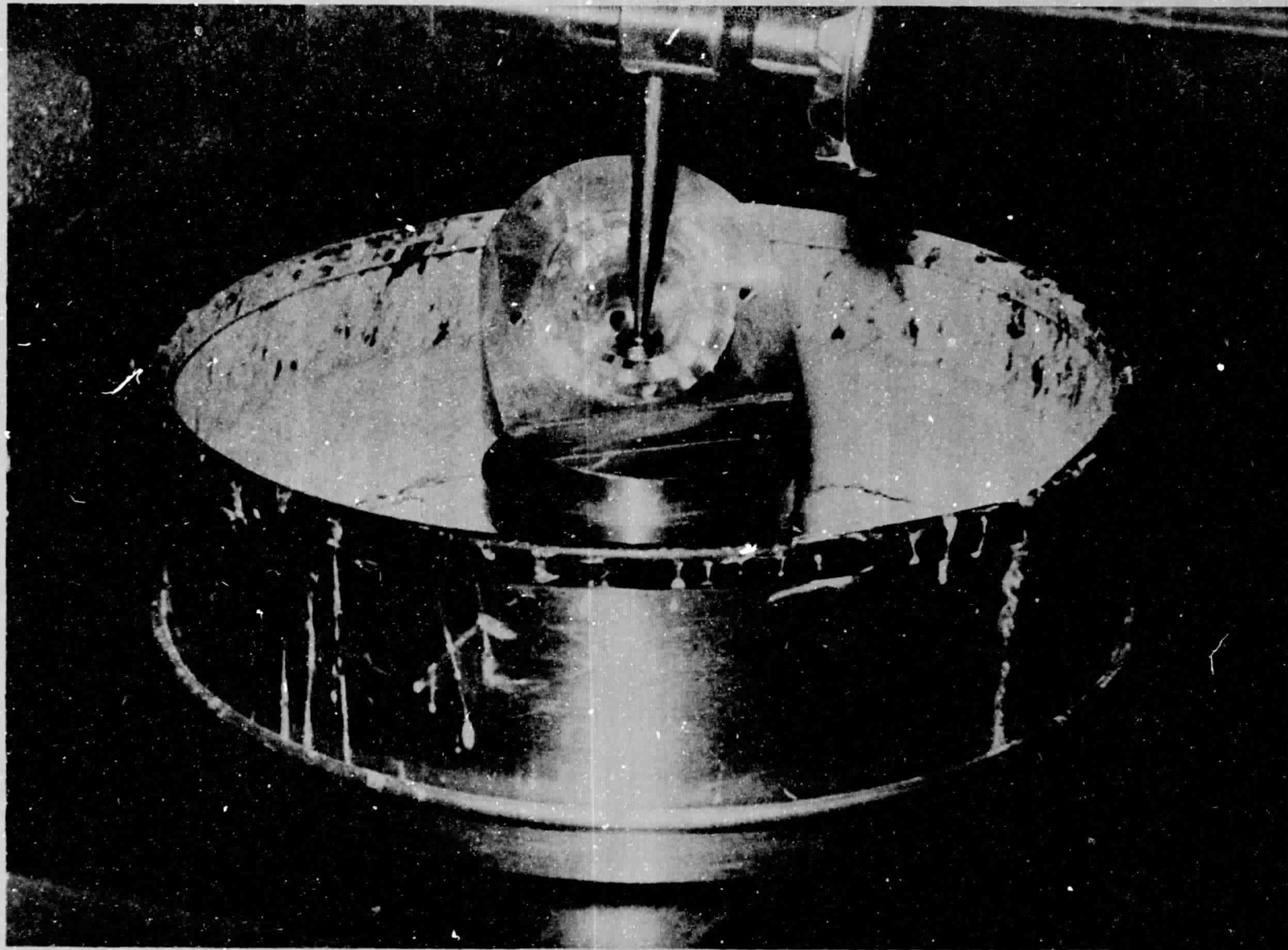

Figure 8. Overall view of measuring procedure.

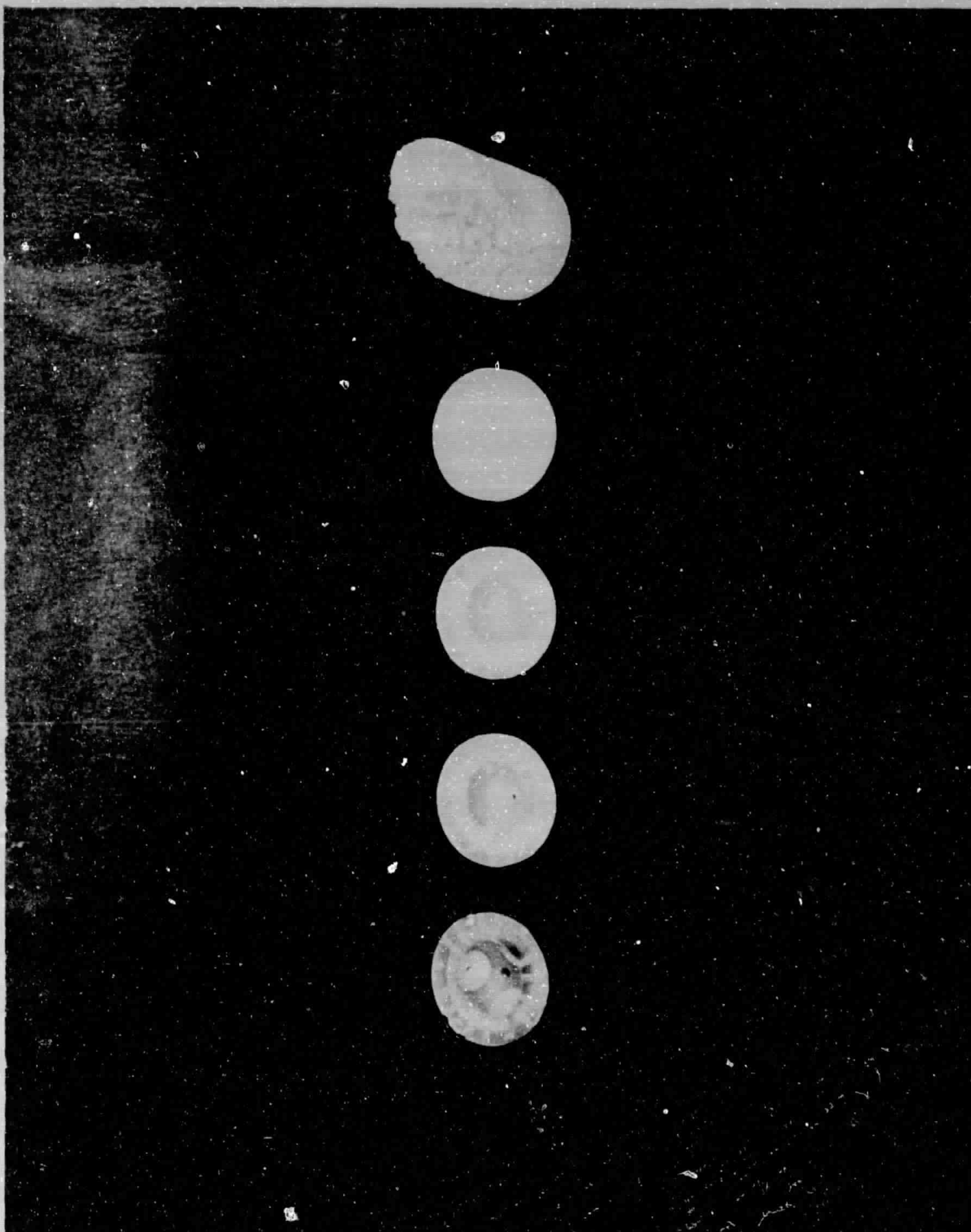

Figure 9. Standard relativity gyro.

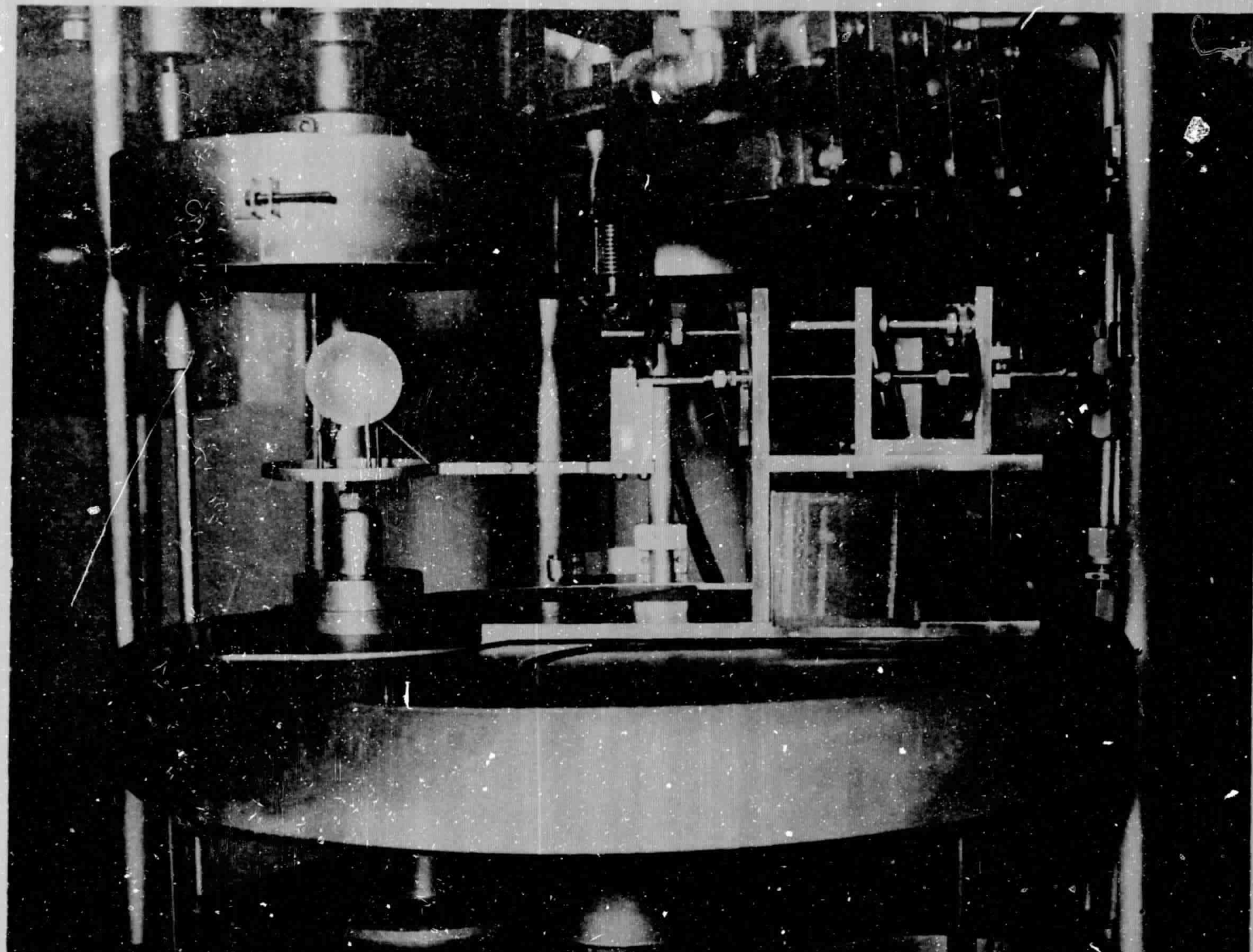

Figure 10. Ball rotating fixture relativity gyro.

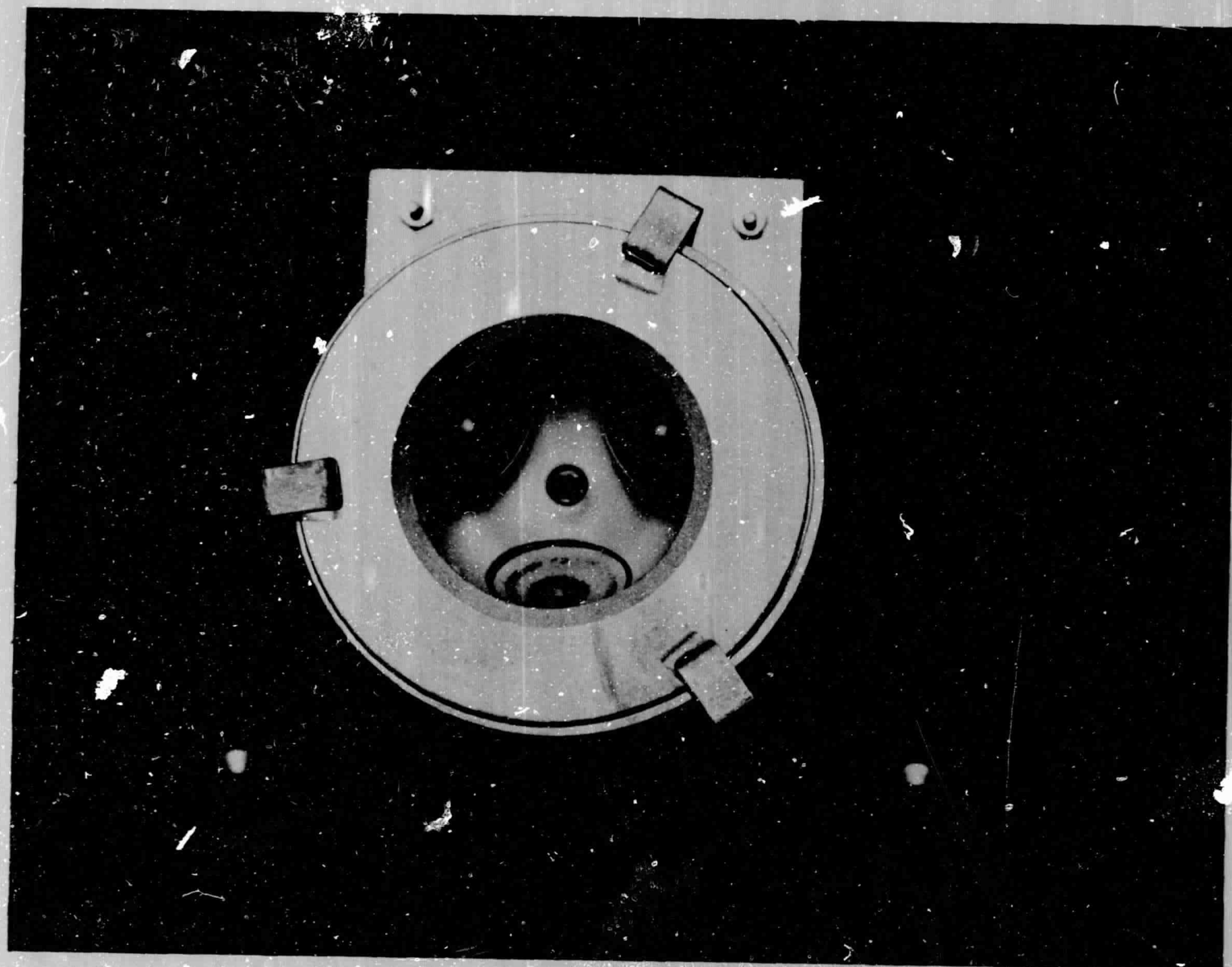

Figure 11. Housing indexing fixture relativity gyro.

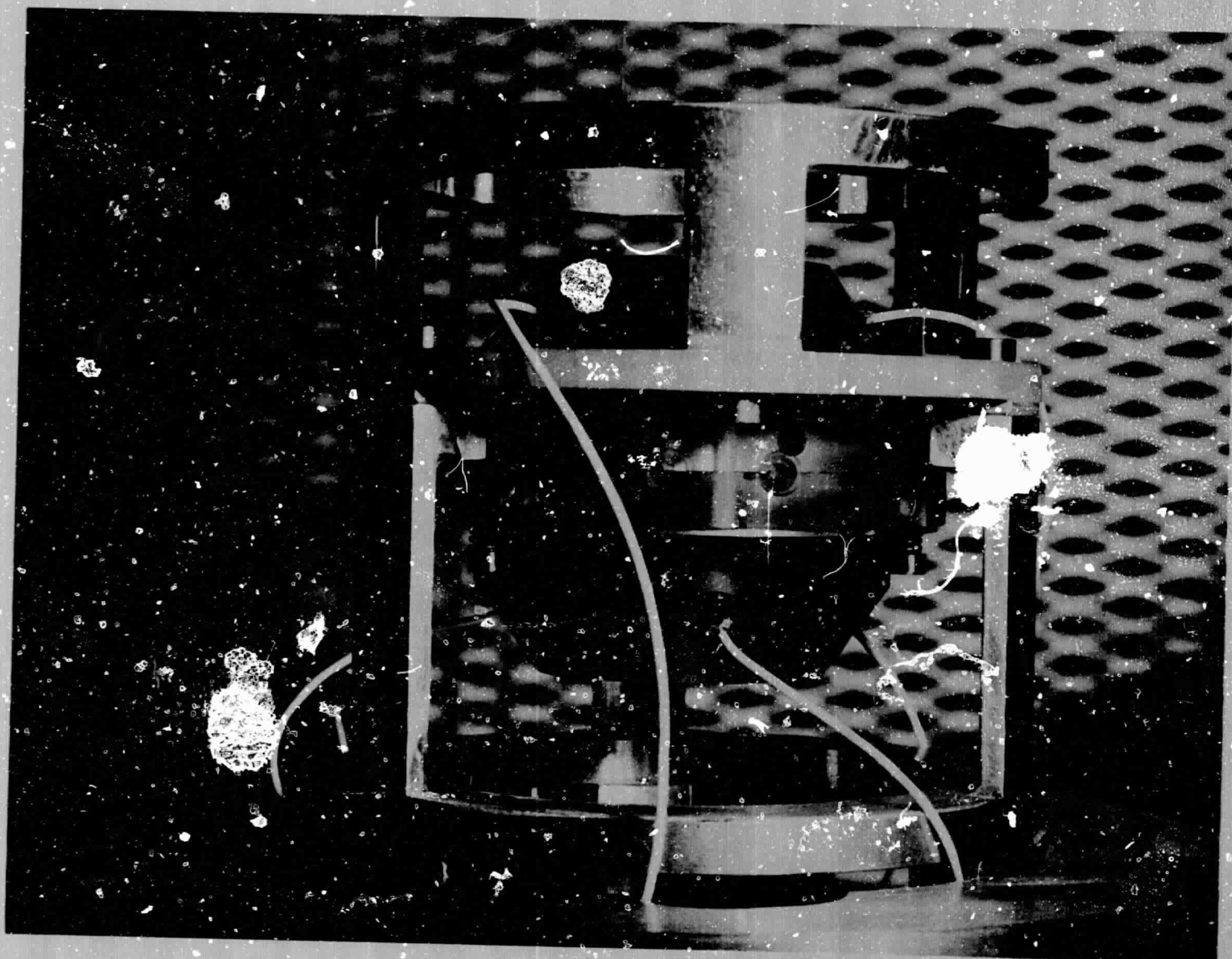

Figure 13. Gravitational Probe "B" relativity gyro No. 1 test assembly.

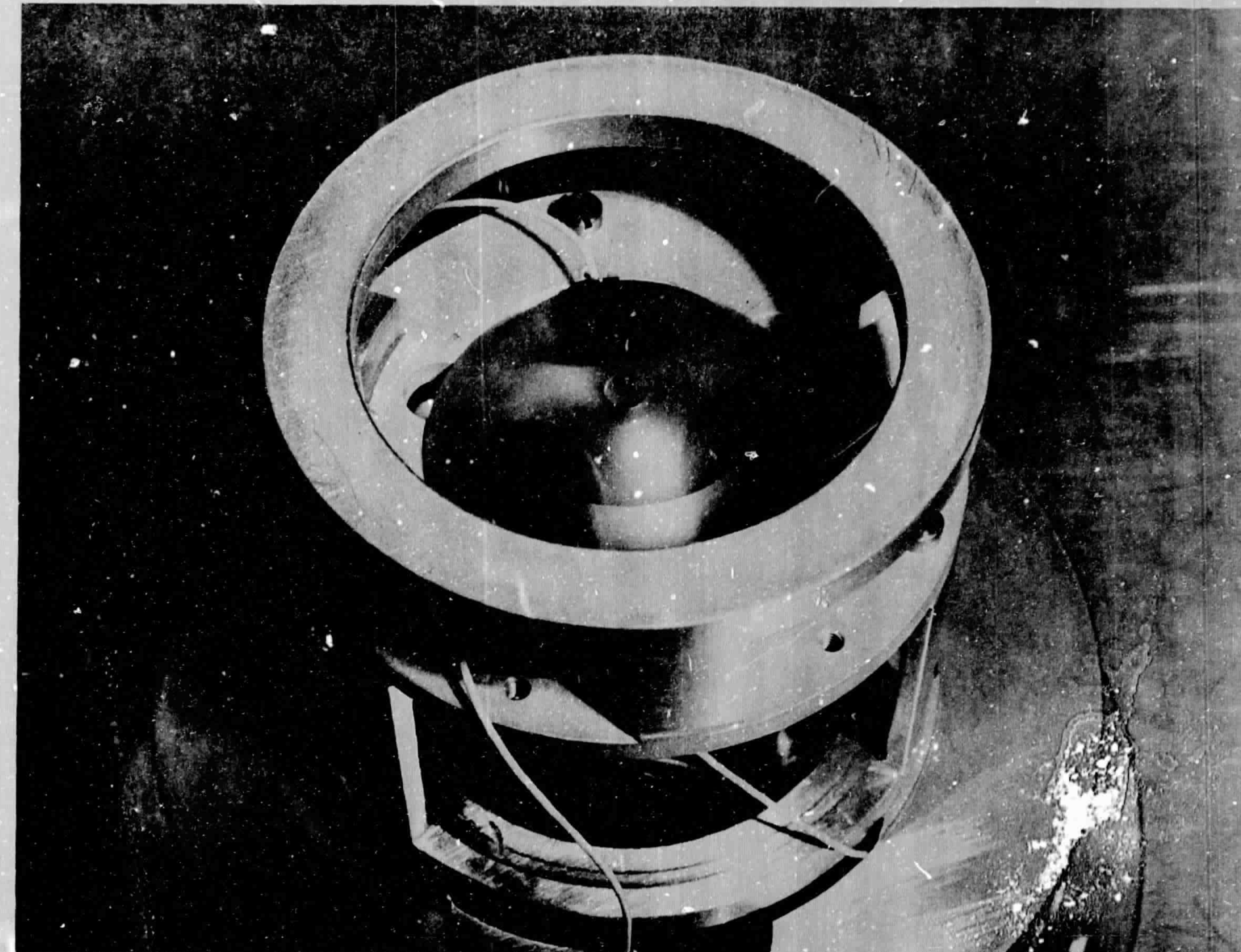

Figure 14. Gravitational probe "B" relativity gyro No. 1 test assembly.

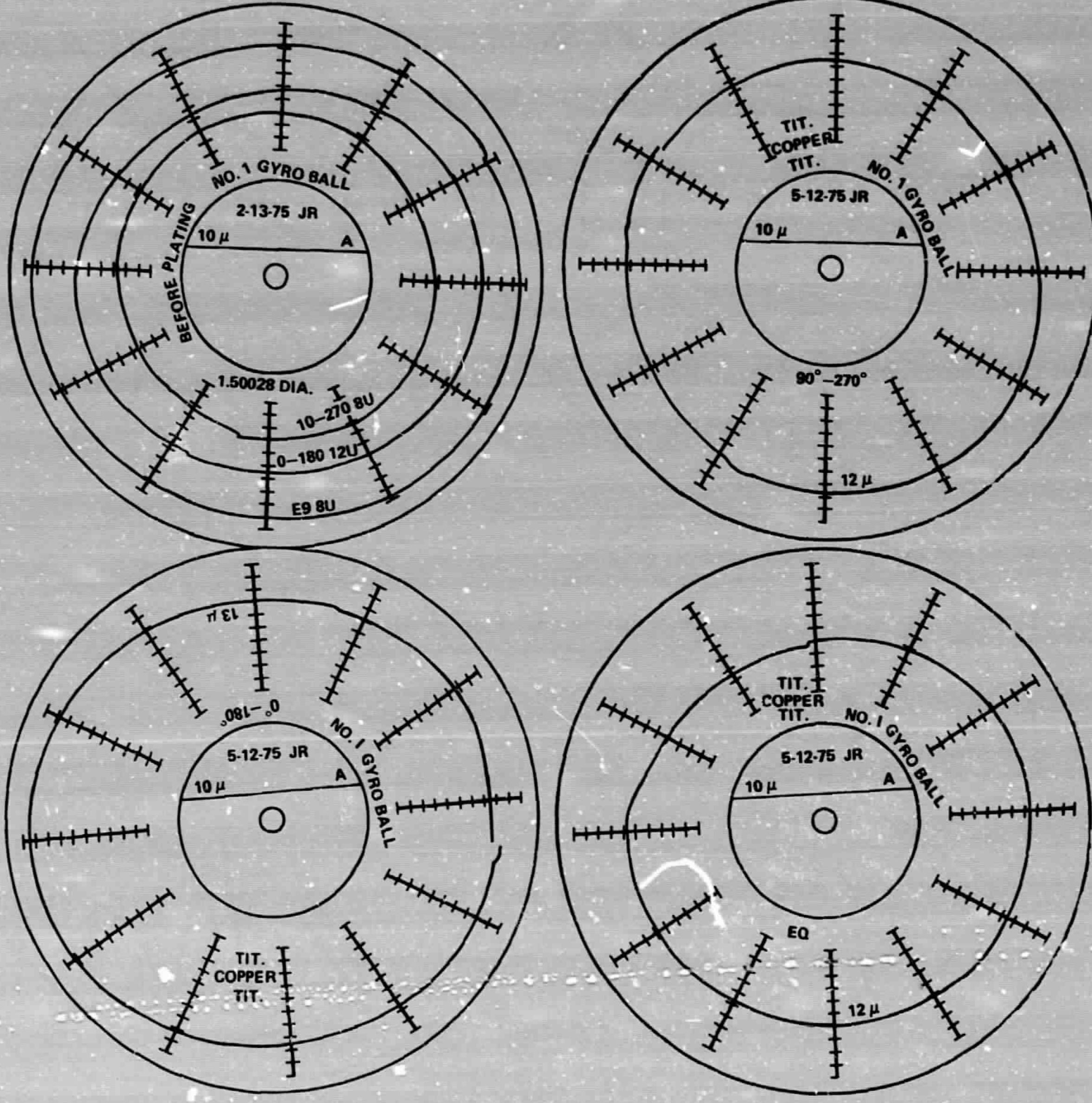

Figure 15. Gyro test.

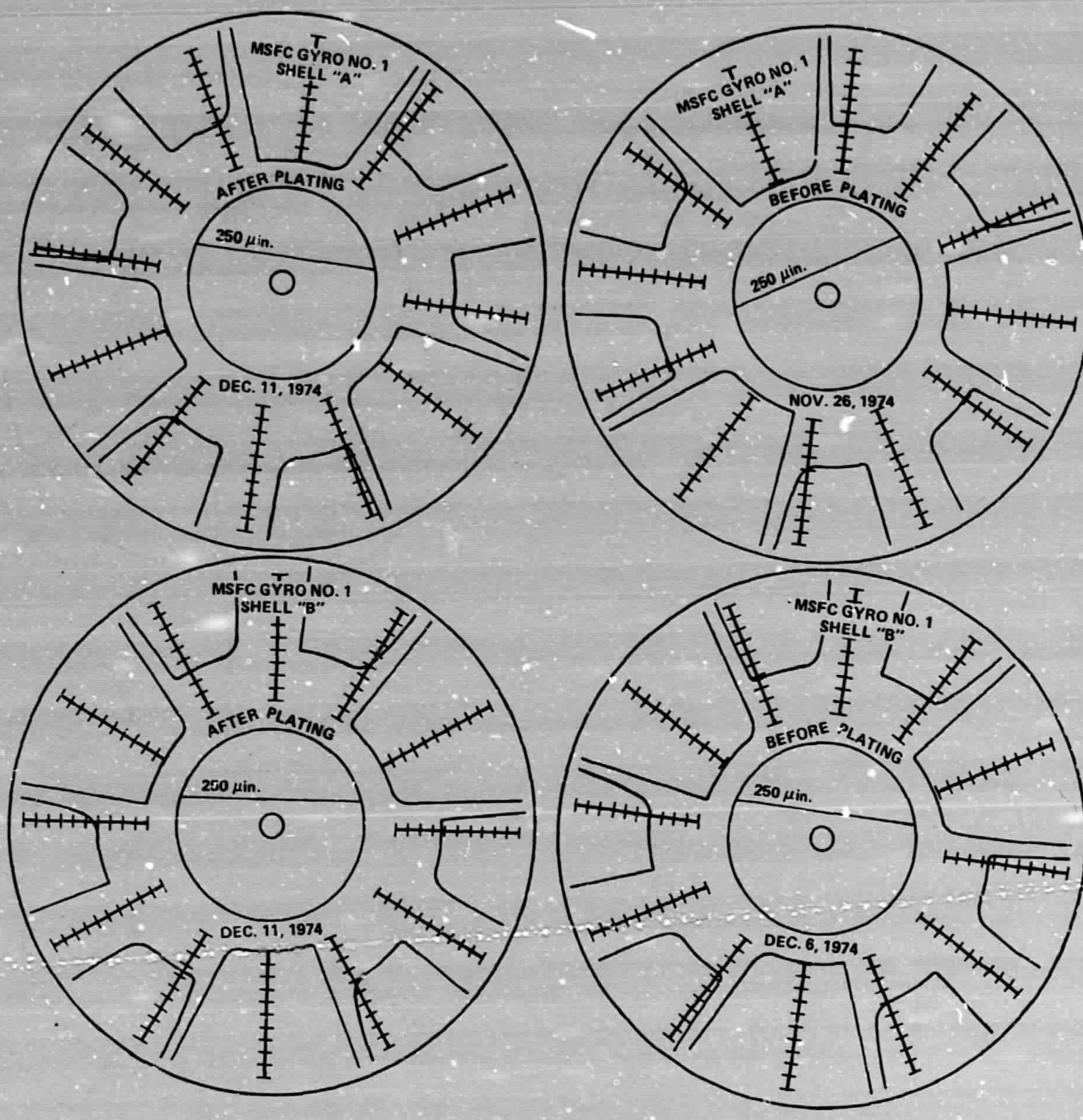

Figure 15. (Concluded)

APPROVAL

MANUFACTURING TECHNIQUES FOR GYROSCOPES IN GRAVITY PROBE B

By John R. Rasquin

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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