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START-STOP TESTING OF TWO SELF-ACTING AIR-LUBRICATED SPIRAL GROOVE THRUST BEARING COATINGS

by

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The Franklin Institute Research Laboratories

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Final Report

By

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16. Abstract

Start-stop tests were conducted on air-lubricated spiral-groove thrust bearings. Application of a matrix-bonded molybdenum disulfide (MoS_2) coating over a porous chrome oxide coating resulted in significantly lower friction, compared to bearings coated with chrome oxide only. The MoS_2 coated bearing sustained 15,000 start-stop cycles at a maximum of 3600 rpm. Each cycle was 15 seconds on, 30 seconds off. The chrome oxide coated bearing failed by local welding after 2030 cycles. Both types of coatings exhibited early failures under higher thrust loads when operating films were insufficient to sustain the load without overheating.

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SUMMARY

The objective of tests conducted for NASA Lewis Research Center was to determine whether a specified design of air-lubricated spiral-groove thrust bearing could withstand 15,000 start-stop cycles. The tests also compared the performance of two surface coatings applied to the thrust bearings.

Four bearing sets were tested. All measured approximately 146 mm active outside diameter and 79 mm inside diameter, and were manufactured of titanium (6Al-4V). The start-stop cycle was 15 seconds on at 3600 rpm, 30 seconds off. Power was applied to the precision motorized spindle mounting the thrust runner. Two thrust loads (A) 44N (10 lb), and (B) 156N (35 lb) were used. Test 1(A) and 1(B) utilized lapped chrome oxide (Cr_2O_3) coatings applied to both bearing and runner. Test 2(A) and 2(B) also used the lapped chrome oxide, with an additional .005 mm thick coating of metal matrix bonded molybdenum disulfide (MoS_2).

Test 1A (Cr_2O_3) failed (by surface welding) after 2030 cycles. Test 2A (Cr_2O_3 + MoS_2) successfully completed 15,000 cycles without failure. The addition of the MoS_2 coating to thrust bearing resulted in significantly lower starting and stopping friction.

Test 1B (Cr_2O_3) 156N thrust load was stopped at 35 cycles after severe welding occurred. Test 2B (Cr_2O_3 + MoS_2) failed after one cycle. Both failures were due to insufficient thickness of operating film at 3600 rpm, which caused local overheating, surface contact, then local welding.

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FIGURES (Cont'd)

FIGURES (Cont'd)

TABLE

1. INTRODUCTION

1.1 GENERAL OBJECTIVES

The application of gas-lubricated bearings to small turboshaft engines has indicated definite promise* . To further quantify feasibility of gas bearings, NASA/Lewis Research Center contracted FIRL (Contract NAS 3-17856) to conduct start-stop tests of air-lubricated spiral-groove thrust bearings designed for the small-turboshaft application. The objective was to determine whether the bearings could survive 15,000 start-stop cycles. The spiral-groove geometry and the bearing and runner materials were specified by NASA/Lewis.

1.2 BEARING GEOMETRY AND MATERIALS

The geometry of the inward-pumping spiral-groove thrust bearings is shown in Figure 1-1. Bearing dimensions are as follows:

Outside diameter	145.80 ± .25 mm	(5.74 ± .01 inch)
Inside diameter	78.74 ± .25 mm	(3.10 ± .01 inch)
No. of spiral grooves		15
Groove angle		162° ± .5°
Groove radial extent	15.50 ± .25 mm	(0.61 ± .01 inch)
Groove depth	0.0305 ± .0050 mm	(0.0012 ± .0002 inch)
Groove width ratio $\left(\frac{\text{groove width}}{\text{groove + land width}}\right)$		0.30 ± .01

Five sample bearings manufactured to conform with the geometry shown in Figure 1-1. Four were tested. The spiral groove geometry was deposited on stress relieved titanium (6Al-4V) using a porous chrome-oxide coating.

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* USAAMRDL Technical Report 71-59

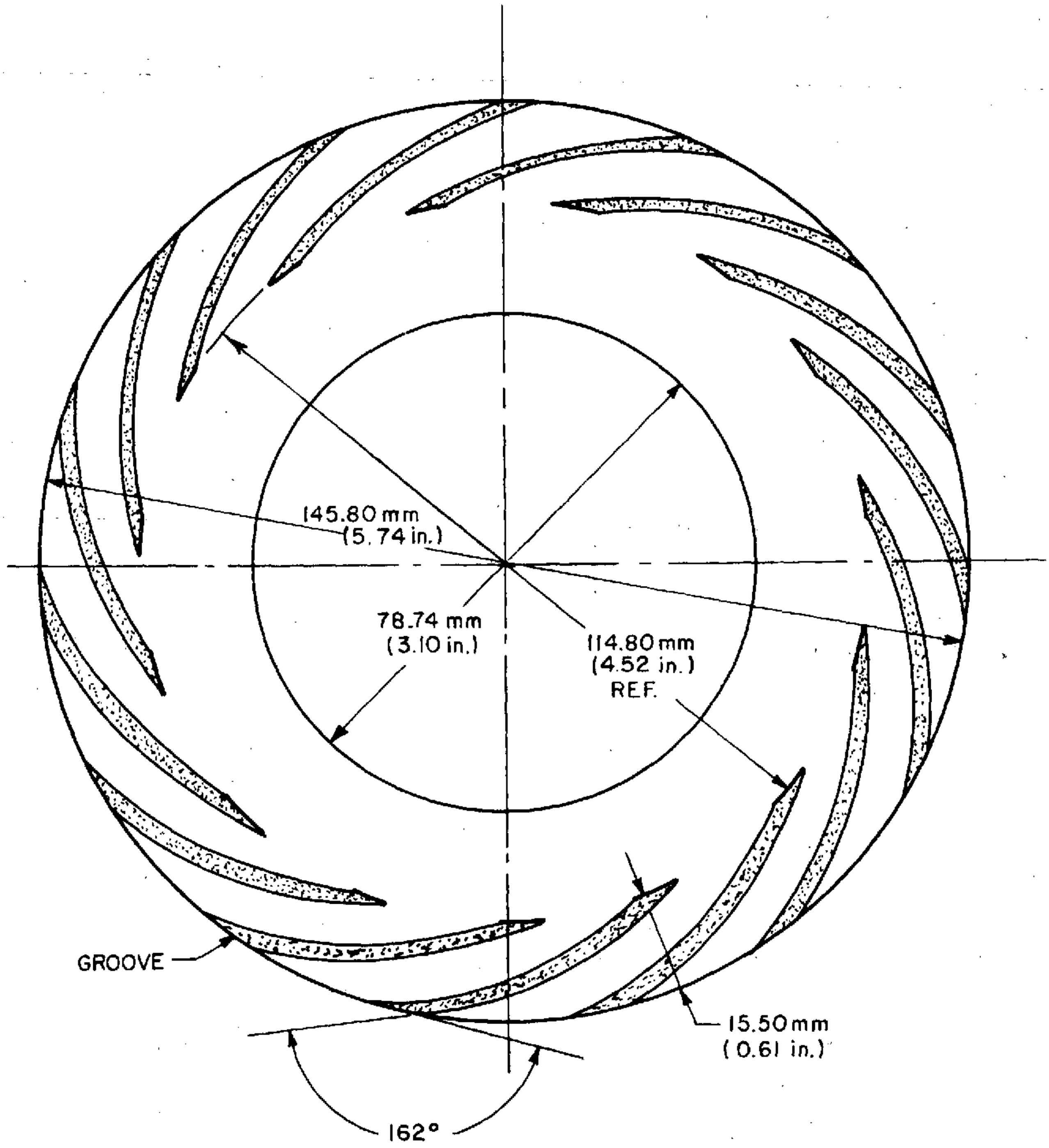

Figure 1-1. Spiral Groove Thrust Bearing Geometry

The runner material was also titanium (6Al-4V). Two chrome-oxide coated bearings were additionally coated with a metal matrix bonded molybdenum disulfide (MoS_2) lubricant approximately .005 mm (0.0002 in) in thickness.

1.3 TESTING

The specified test procedure was as follows:

a. Photograph and take surface finish test on each bearing specimen before test.

b. Run 15,000 start-stop cycles (or until failure). Tests to be conducted as follows:

   1. Cr_2O_3 coated bearing, 44N (10 lbf) load
   2. Cr_2O_3 coated bearing, 156N (35 lbf) load
   3. Cr_2O_3 and MoS_2 coated bearing 44N (10 lbf) load
   4. Cr_2O_3 and MoS_2 coated bearing 156N (35 lbf) load

   Cycle time - 15 seconds on, 30 seconds off for a total of 45 seconds

   Cycles stop at 1000 cycle intervals for photographs and surface finish measurements. Inspection of the surface for signs of wear.

   Record surface deterioration with photographs when deemed necessary.

c. Make final examination of completion of testing.

With the load applied the speed was varied from 0 to 3600 rpm over each start-up and shut-down cycle. Bearing failure was defined as a seizure or inability to generate a hydrodynamic film at the maximum test speed of 3600 rpm.

2. RESULTS AND CONCLUSIONS

Two test series were performed. The first test series (1A and 1B) utilized chrome oxide coated bearings, and the second test series (2A and 2B) utilized chrome oxide + molybdenum disulfide coated bearings. The first test (1A), using a lapped chrome oxide coated thrust bearing, completed 2030 start-stop cycles (15 sec.on, 30 sec.off) with a 44N (10 lbf) thrust load before the bearing seized. (Failure is defined as a seizure or inability to generate a hydrodynamic film at test speed of 3600 rpm.) A wear pattern with a depth of .0013 mm (.000050 in) was measured just before failure occurred. A second 44N (10 lbf) thrust load test (2A) was accomplished, using a similarly coated spiral groove bearing, but with an additional .005 mm (.0002 in) layer of metal matrix bonded molybdenum disulfide lubricant (Hohman Surf-Kote M-1284). This surface coating has a surface quality and appearance inconsistent with the usual exacting air bearing accuracy and finish specifications. Nevertheless 15,000 start-stop cycles were completed using the 44N (10 lbf) thrust load with no marked change in the finish or appearance of the coating, except for a few burnished areas.

A 156N (35 lbf) thrust load start-stop test (1B) using a chrome oxide coated bearing failed at 35 cycles. The maximum running speed of 3600 rpm gave a bearing clearance of less than .0038 mm (.00015 in) (compared to a .0064 mm (.00025 in) to .0076 mm (.0003 in) for the 44N (10 lbf) tests). Excessive temperature rise (greater than 50K (90°F)) in the ungrooved inner diameter of the bearing expanded the material locally, causing the surfaces to rub. Then, generation of coating debris at the contact area separated the bearing and thrust runner by .025 mm (.001 in) before automatic shut off occurred. A similar test (2B), using a thrust bearing with the Surf-Kote coating failed after 30 seconds of running time. In both cases (1B and 2B), failure was due to the bearings' inability to generate sufficient running clearance at 3600 rpm (under the 156N (35 lbf) load) to maintain low operating temperatures. Local overheating caused contact of the bearing surfaces and subsequent failure. The fact that the bearing in test 2B (MoS_2 coated) failed at one cycle, rather than the 35 cycles of 1B is probably due to the lack of flatness in the MoS_2 coating.

A summary of the results of the four start-stop tests conducted on the air thrust bearings is shown in Table 2-1. Figure 2-1 shows the running clearance, with starting and stopping torques for a chrome-oxide bearing with a 44N (10 lbf) thrust loading, Bearing #5, Test 1A. Figure 2-2 shows the running clearance, with starting and stopping torques for a MoS_2 coated bearing with 44N (10 lbf) thrust loading, Bearing #1, Test 2A.

Comparing the results, the following conclusions can be drawn:

1. The metal matrix-bonded molybdenum disulfide coated bearing has lower starting and stopping torques for the 44N (10 lbf) load. The bearing can sustain 15,000 start-stop cycles.

2. With a 156N (35 lbf) load, the bearing design has insufficient running clearance at 3600 rpm. A higher rpm must be used in order to obtain a clearance sufficient to prevent local overheating, and rubbing contact of the bearing surfaces.

3. Insufficient data was obtained to predict whether the molybdenum disulfide coating would be superior at the higher unit loadings.

4. In a thrust bearing of this size, running clearances under .005 mm (.0002 in) are not recommended, since overheating and other failure modes can easily occur. Runouts of the thrust runner less than .0025 mm (.0001 in) can be attained only with careful adjustment and/or hand fitting.

Table 2-1. Summary of Start-Stop Tests

Test	Bearing Set Number	Thrust Load	Running Clearance[1]	Temp. Rise[2]	Starting Torque	Stopping Torque	Cycles to Failure	Measured Wear
1A	Cr_2O_3 Coated 5	44N (10 lb)	.006-.0076mm (.00025-.0003 in)	5.6 K (10°F)	2 N-m (18 in-lbs)	2.5 N-m (22 in-lb)	2030	.0013mm (50μ in)[5]
1B	Cr_2O_3 Coated 3	156N (35 lb)	.0038mm (.00015in)	50 K 90°F[3]			35	.025mm (.001 in)[6]
2A	MoS_2 Coating 1	44N (10 lb)	.006-.0076mm (.00025-.0003 in)	5.6 K (10°F)	.34-.45N-m (3-4 in-lbs)	.34-.45 N-m (3-4 in-lbs)	15,000[4]	<.00065mm (<25μ in)[7]
2B	MoS_2 Coating 2	156N (35 lb)	.0038mm (.00015 in)	50 K 90°F			1	.025mm (.001 in)

(1) At 3600 RPM
(2) After 1 hour running time
(3) Before automatic shutoff occurred
(4) No failure
(5) Before failure occurred
(6) After failure occurred
(7) Estimated

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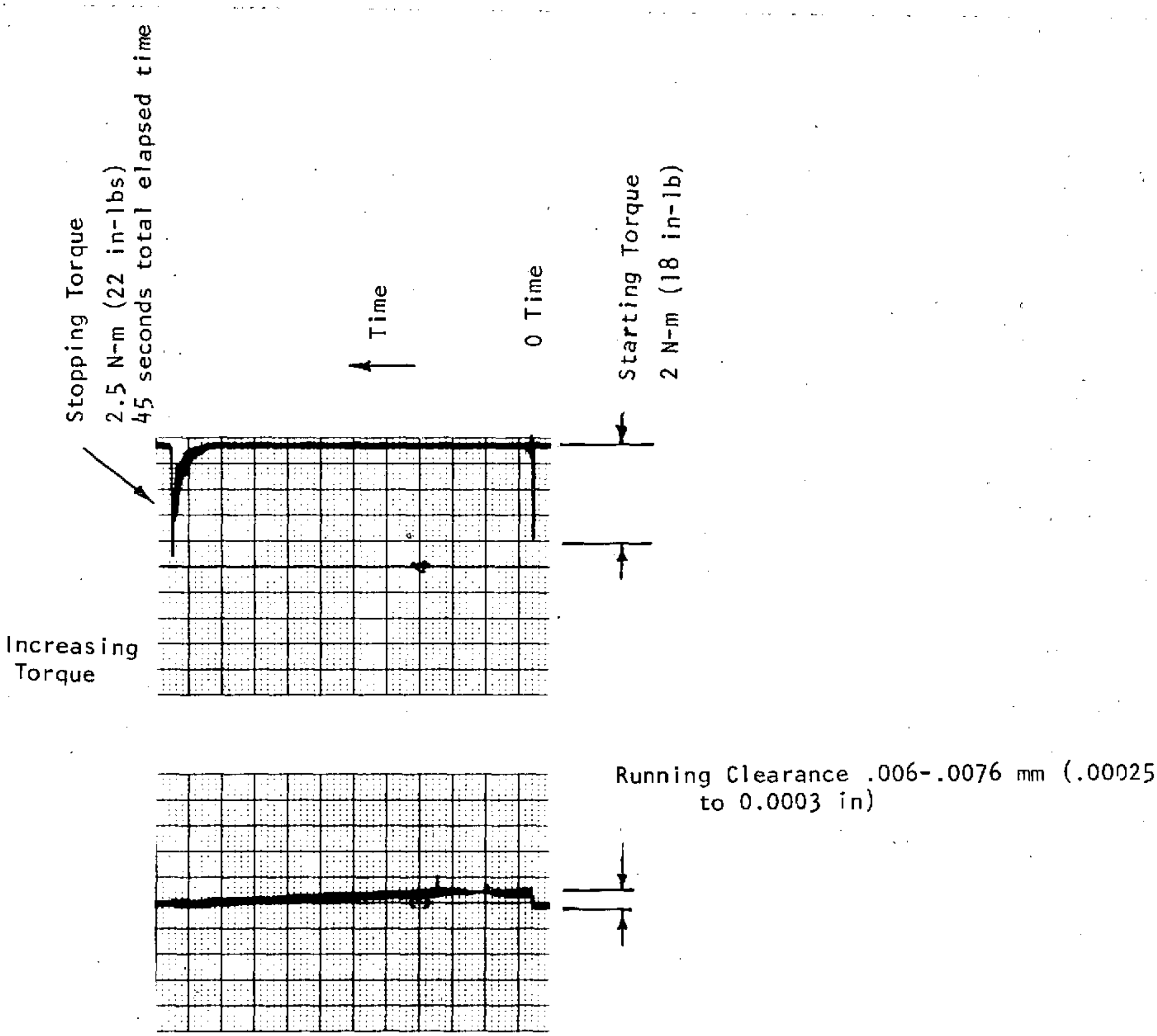


Figure 2-1. Test 1A, Bearing No. 5, Running Clearance vs. Time, Chart Records With Starting and Stopping Torques, 44N (10 lbf) Load, Cr_2O_3 Coating Only.

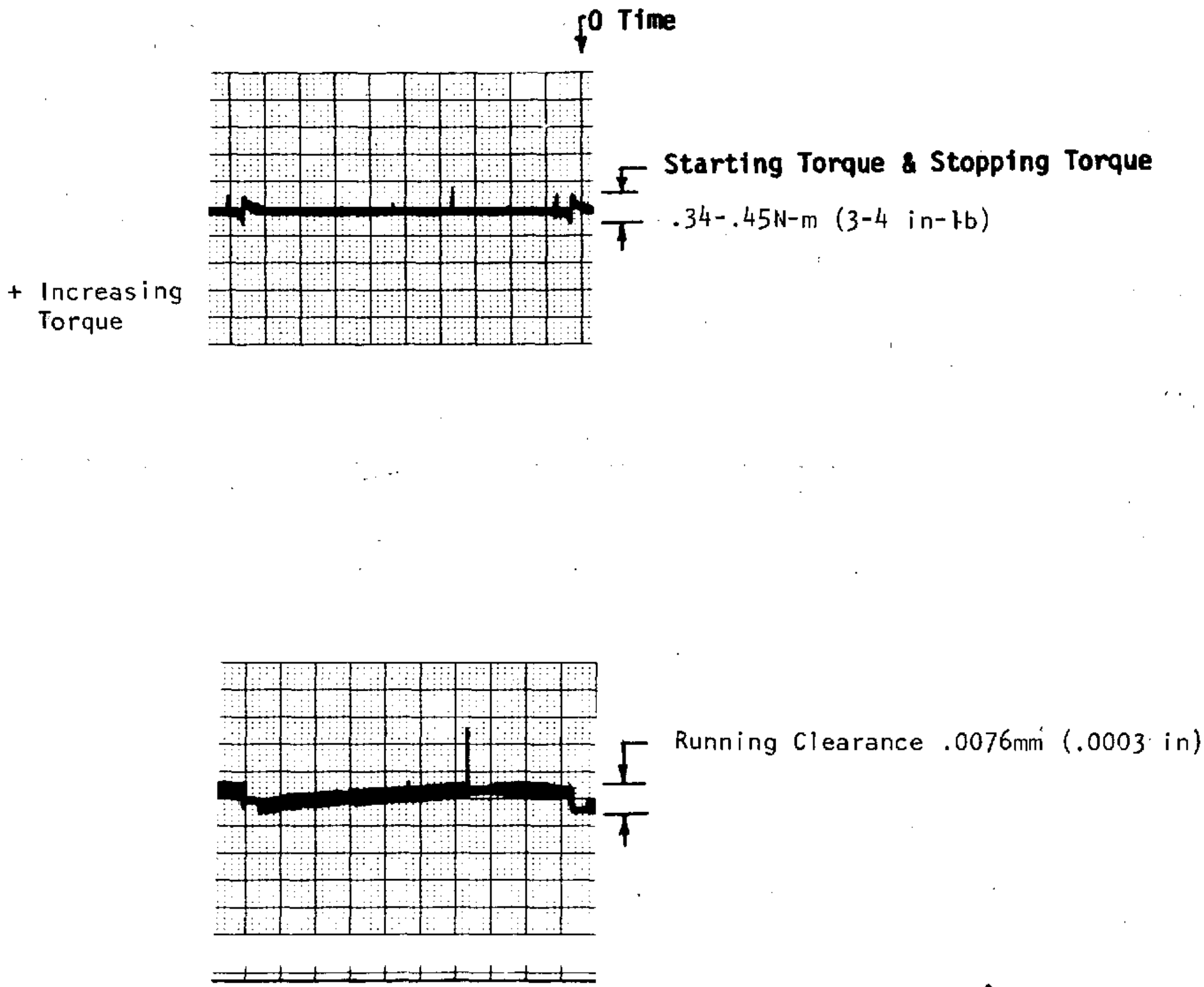


Figure 2-2. Test 2A, Bearing No. 1, Running Clearance vs. Time, Chart Records With Starting and Stopping Torques, 44N (10 lbf) Load, $Cr_2O_3 + MoS_2$ Coating

3. RECOMMENDATIONS

1. Test a molybdenum disulfide coated bearing at a more compatible load-speed condition than the 156N (35 lbf) 3600 rpm previously specified, since this is beyond the capability of the spiral-groove bearing design. Since in the actual turbomachine, speeds in excess of 3600 rpm will occur, the most logical approach is to increase operating speed.

2. This type of thrust bearing (spiral groove) does not display good moment loading characteristics. Local deformation and misalignments, whether built in initially, or caused by temperature gradients or stress relieving, are likely to cause early failures. Two approaches to the problem are suggested:

   a. A revision of the present design to a design such as shown in Figure 3-1. First an undercut area is provided to permit free flow of inward pumped air. Next "donor" areas are coated with molybdenum disulfide to a height of about 2/3 of the normal operating film. Care must be taken so as not to permit runout of the bearing O.D. to exceed this coating height. Also overheating must also be avoided in the areas. The idea is to provide a wear surface which can slowly abrade away without affecting the bearing characteristic geometry.

   b. A resiliently mounted carbon-shoe tilting pad bearing like that shown in Figure 3-2 can sustain greater thrust loading and misalignment than conventional spiral-groove thrust bearings.

3. FIRL has long advocated tilting pad bearings with inherent self-aligning and cooling capabilities, as being much more adaptable to turbomachinery applications. Over recent years we have been developing compliant mounted bearings with very encouraging results. Figure 3-2 shows the compliant mounted thrust bearing configuration. The pads are supported by a compliant elastomer that permits pitch and roll of the pads, and through the local axial compliance of the elastomer also provides load equalization on the various pads.

   FIRL has accomplished start-stop testing with 48 kilonewtons per square meter (7 psi) unit loading on a tilt-pad compliant mounted thrust bearing with negligible wear. The spiral groove bearing discussed in this report could not accept 14 kilonewtons per square meter (2 psi) unit loading.

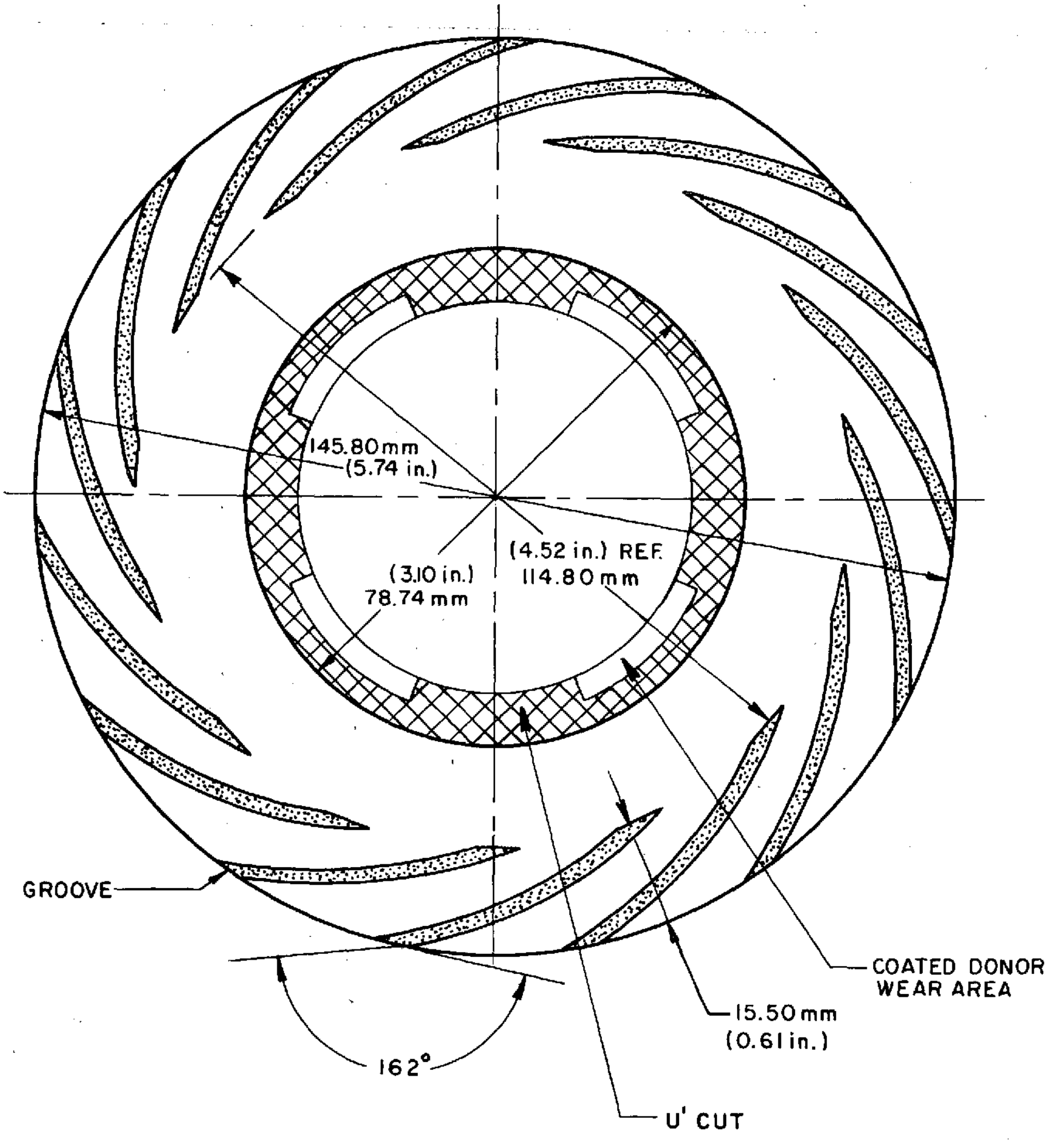


Figure 3-1. Spiral Groove Thrust Bearing With Donor Wear Areas

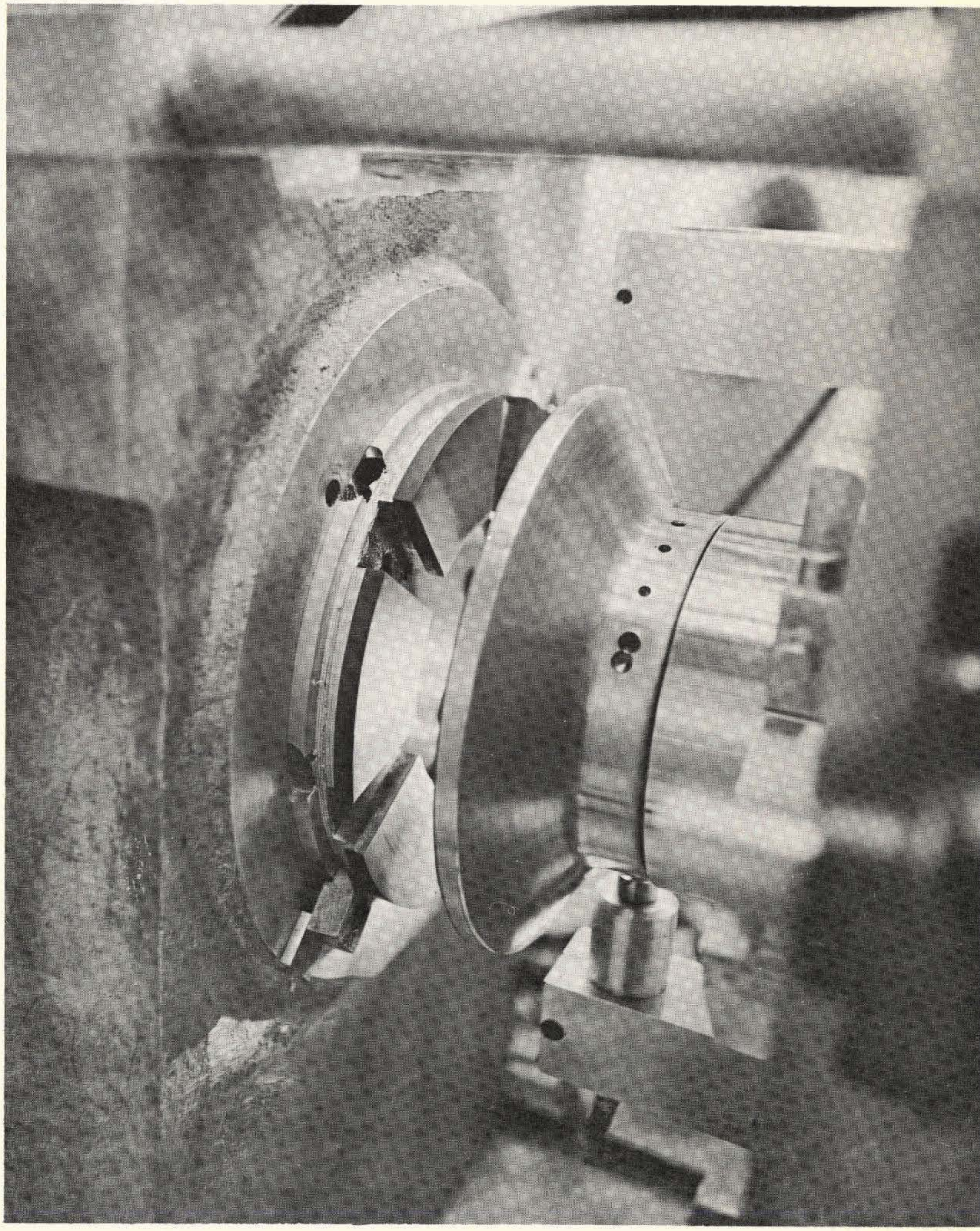


Figure 3-2. Compliant-Mounted Pad Type Thrust Bearing Installed in Test Rotor Assembly

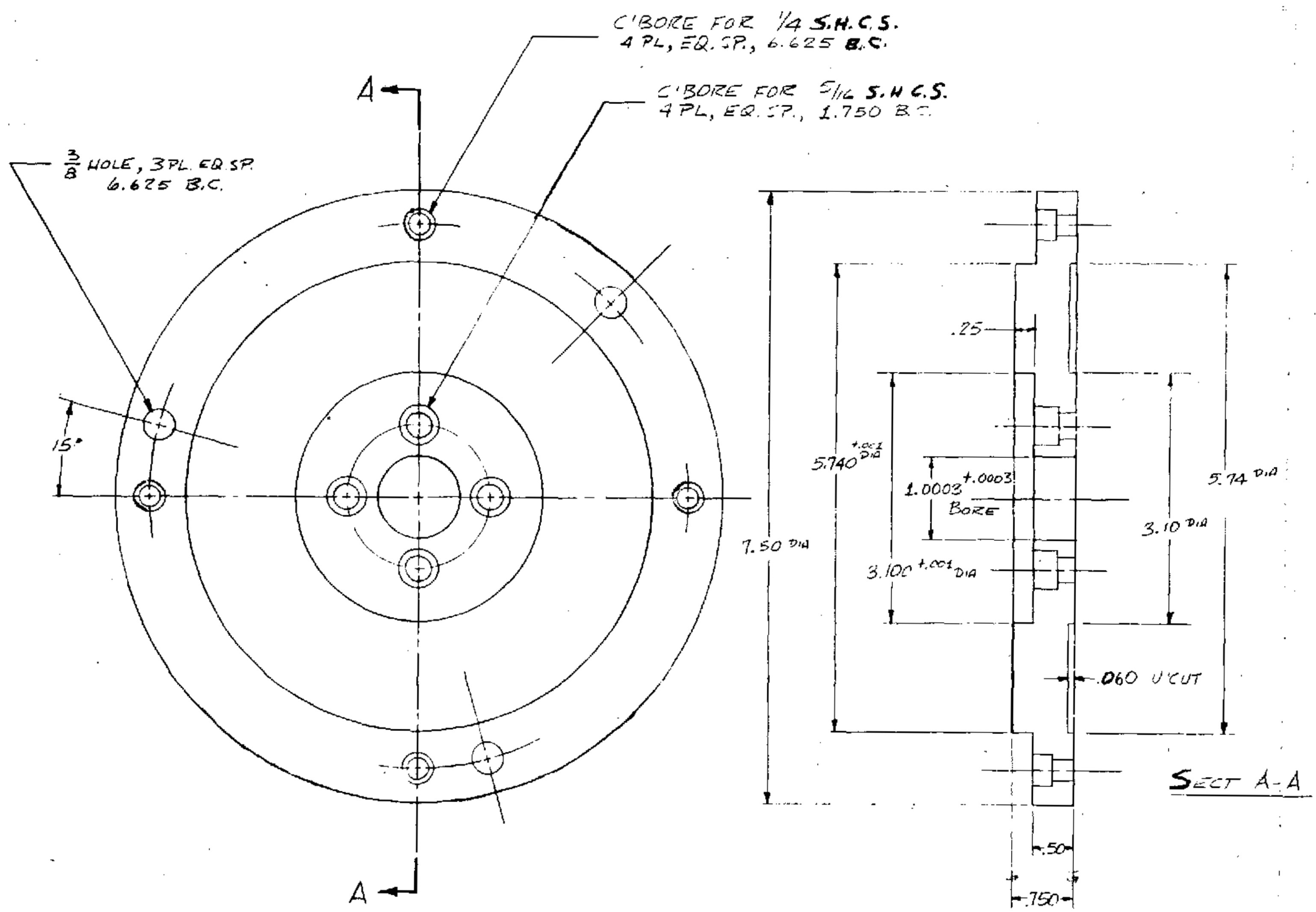
If conventional elastomers are employed then ambient temperature would be limited to 422K (300°F). With advanced elastomeric materials and/or composites, the useful range could be extended to 589K (600°F) or 644K (700°F). It is recommended that a compliant mounted thrust bearing be designed, manufactured and tested for this application.

4. BEARING MANUFACTURE

Figure 4-1 shows the dimensions of the stationary member (spiral groove bearing) and the thrust runner. Both members were manufactured from 20.6 mm (.81 in) thick titanium (6Al-4V). After rough machining, the titanium was stress relieved by heating to 810K (1000°F) for four hours, then air cooled. It was decided that an aluminum spray mask (Figure 4-2) would be used to obtain the necessary coating of porous chrome oxide between the grooves. The faces of the titanium were carefully ground flat, since concavity in the bearing face would preclude the possibility of maintaining the groove depth to the tolerance desired.

The spray coating of porous chrome oxide was applied by Hohman Plating, Dayton, Ohio. As received from Hohman, the titanium plates proved to have been slightly warped by the coating process. The warpage amounted to .005 mm (.0002 in). Such deformation, while ordinarily considered small, had to be corrected because it was the same order of magnitude as the operating clearance under the high-load condition. The backs of the titanium bearings and runners were machine lapped flat, and the chrome oxide faces were then diamond ground and lapped by Stein Seal of Philadelphia. Measurement of the surface finish and groove depth of bearings was accomplished by FIRL using a Gould Surfanalyzer. The desired surface finish of 0.25 micrometers (10μ inches) AA [(1)] was obtained. The average groove depth was within tolerance, although it was possible to find some areas with slightly deeper grooves. Such a condition is difficult to correct, since some warping of the titanium is inevitable, and the groove roughness (caused by the surface preparation used to promote adhesion) has undulations on the order of .005 mm (.0002 in.)

(1) AA is arithmetic average obtained by drawing a center line thru the surface profile, then averaging weights of peaks and valleys to both sides of center line. British use CLA (Center line average), perhaps a more descriptive term for the identical measurement system.



NOTES: 1. Stress Relieve Rough Machined Blank 4 Hours @ 810K (1000°F), Air Cool

Figure 4-1. Bearing and Runner Dimensions,(a) Bearing

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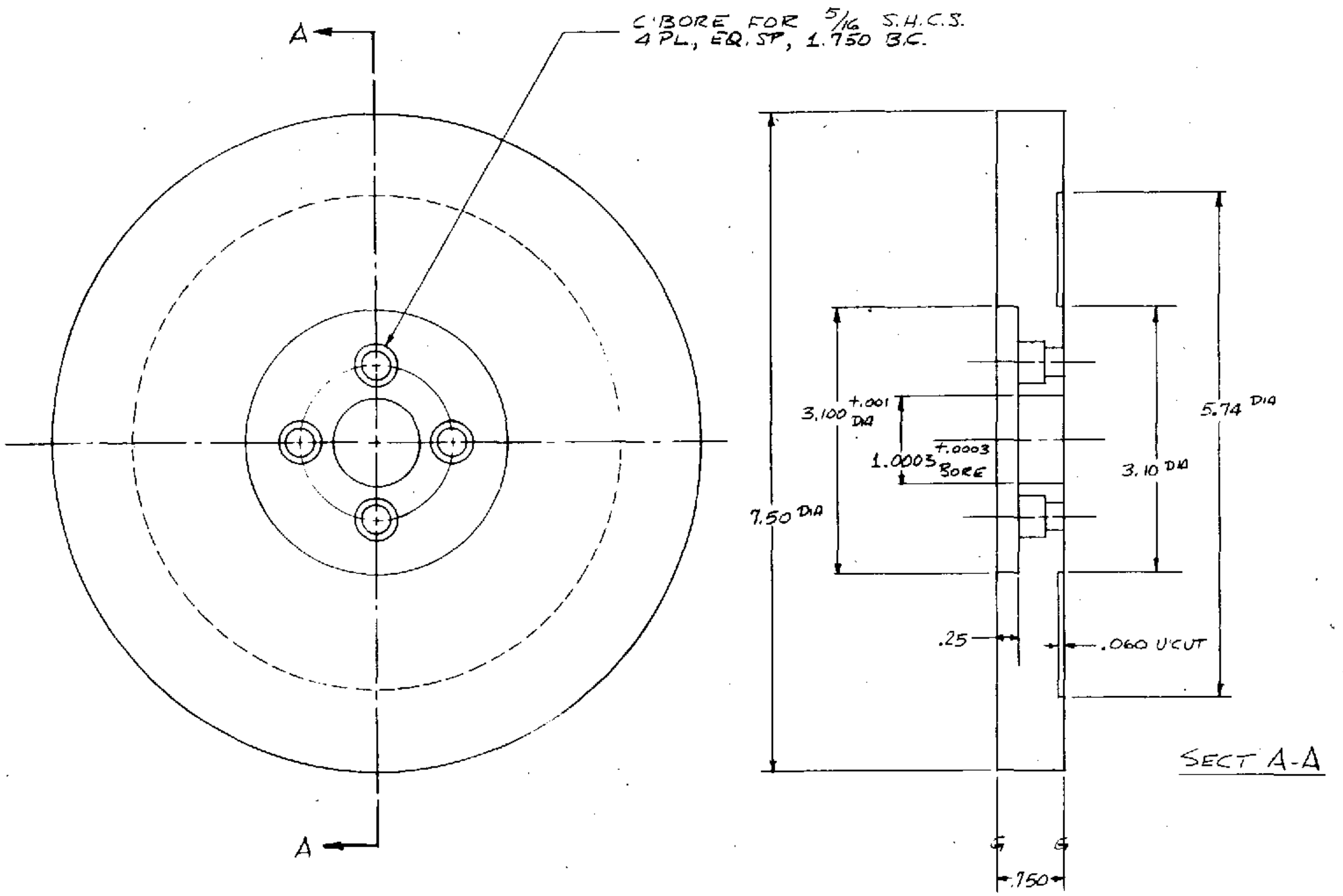

NOTES: 1. Stress Relieve Rough Machined Blank 4 Hours @ 810K (1000°F), Air Cool

Figure 4-1. Bearing and Runner Dimensions (Cont'd), (b) Runner

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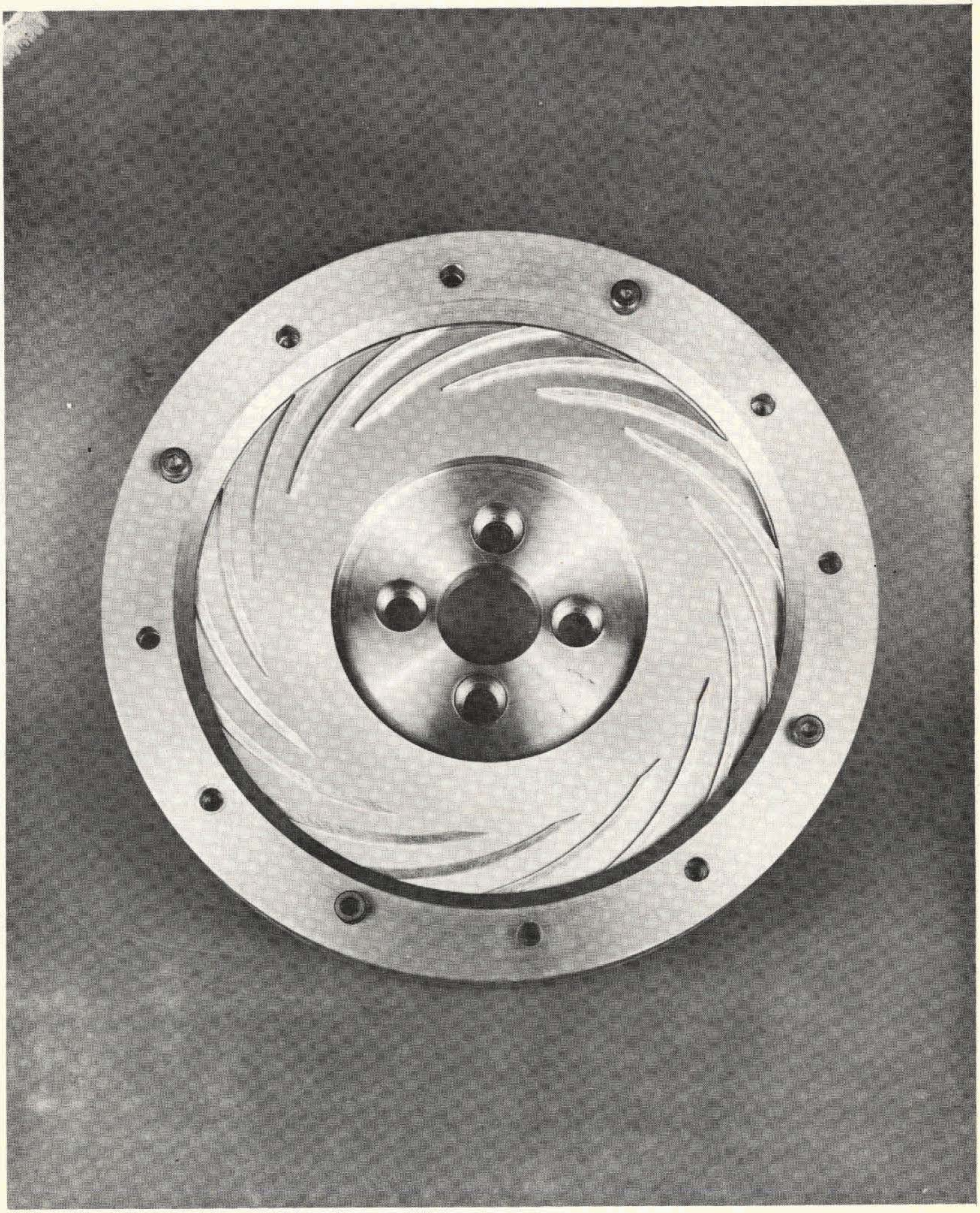

Figure 4-2. Spray Mask and Holding Fixture, in Position on Thrust Bearing, Ready for Coating

Two sets of the chrome oxide coated and lapped bearings were then coated by Hohman Plating with Surf Kote M-1284, a metal matrix bonded molybdenum disulfide lubricant. The coated bearings were inspected by FIRL. The surface finish was 2.5-3.8 micrometers (100-150μ inches) AA, and the coating thickness varied. It was perhaps .0076 mm (.003) thicker at the O.D. than at the I.D. The coating was very carefully ground flat to within .0013 mm (.00005 in) and the deposits in the grooves scraped clean. Surface finish was again taken, averaging 1.3-2.5 micrometers (50-100μ in) AA. Finished groove depth was not measured, since surface roughness of both the MoS_2 coating and the bottom of the grooves precludes accurate readings. For groove depth before MoS_2 coating was applied, see appropriate chart for bearing set, Figures 7-20 and 7-28.

5. DESCRIPTION OF BEARING TESTING MACHINE AND TEST ARBOR

The bearing tester Figure 5-1 and Figure 5-2 is a Bridgeport milling machine base on which is mounted a direct drive 5 hp superprecision spindle manufactured by Whitnon. The No. 40 N.M.T. taper nose was precision ground on its own bearings to obtain a runout of less than .0025 mm (.0001 in) F.I.R. The test thrust runners were mounted on an ultra-precision arbor (Figure 5-3) fitted to the spindle nose. The runner was clamped to the face of the arbor using four 5/16-18 socket head cap screws. Tightening of the cap screws was performed while monitoring the runout with an electronic dial indicator. Runouts of .0013 mm (50μ in) F.I.R. were obtainable, but only with great care.

The thrust bearing is mounted to a subplate which in turn is attached to the air bearing load cell with elastic hinges to permit precise alignment. The combination loading device and thrust torque transducer is self-aligning, and its mass and damping characteristics prevent the occurrence of resonances. Alignment of the thrust bearing to the spindle rotation was also adjusted to .0013 mm (50μ in) F.I.R.

Three capacitance probes were used to obtain the air thrust bearing operating clearance. They were located outside of the active bearing diameter. Two thermocouples, one located near the entrance to the bearing O.D. and the other positioned to obtain the air exit temperature were used. A strain gage torque arm gave starting and stopping torques and perturbations. Automatic recording of the data was accomplished on a 6-channel Brush recorder and a Honeywell temperature recorder.

An automatic control system turned on the motorized spindle which obtained the maximum speed of 3600 rpm in less than one second. Running time was 15 seconds, then power to the spindle was removed and dynamic braking applied to stop the spindle rotation completely in 25 to 28 seconds. At the end of the 45 second cycle, power to the motor is again

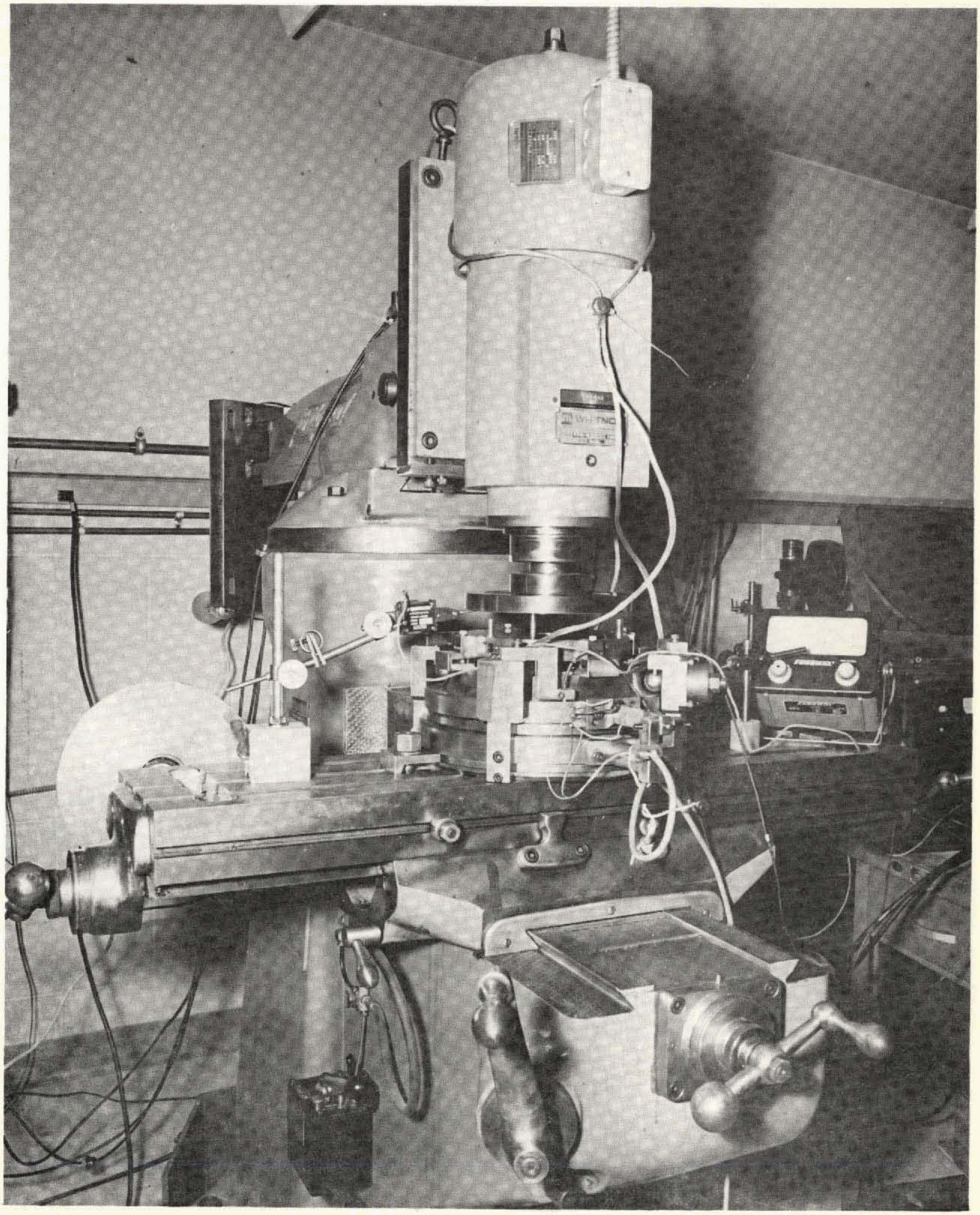

Figure 5-1. Thrust Bearing Testing Machine

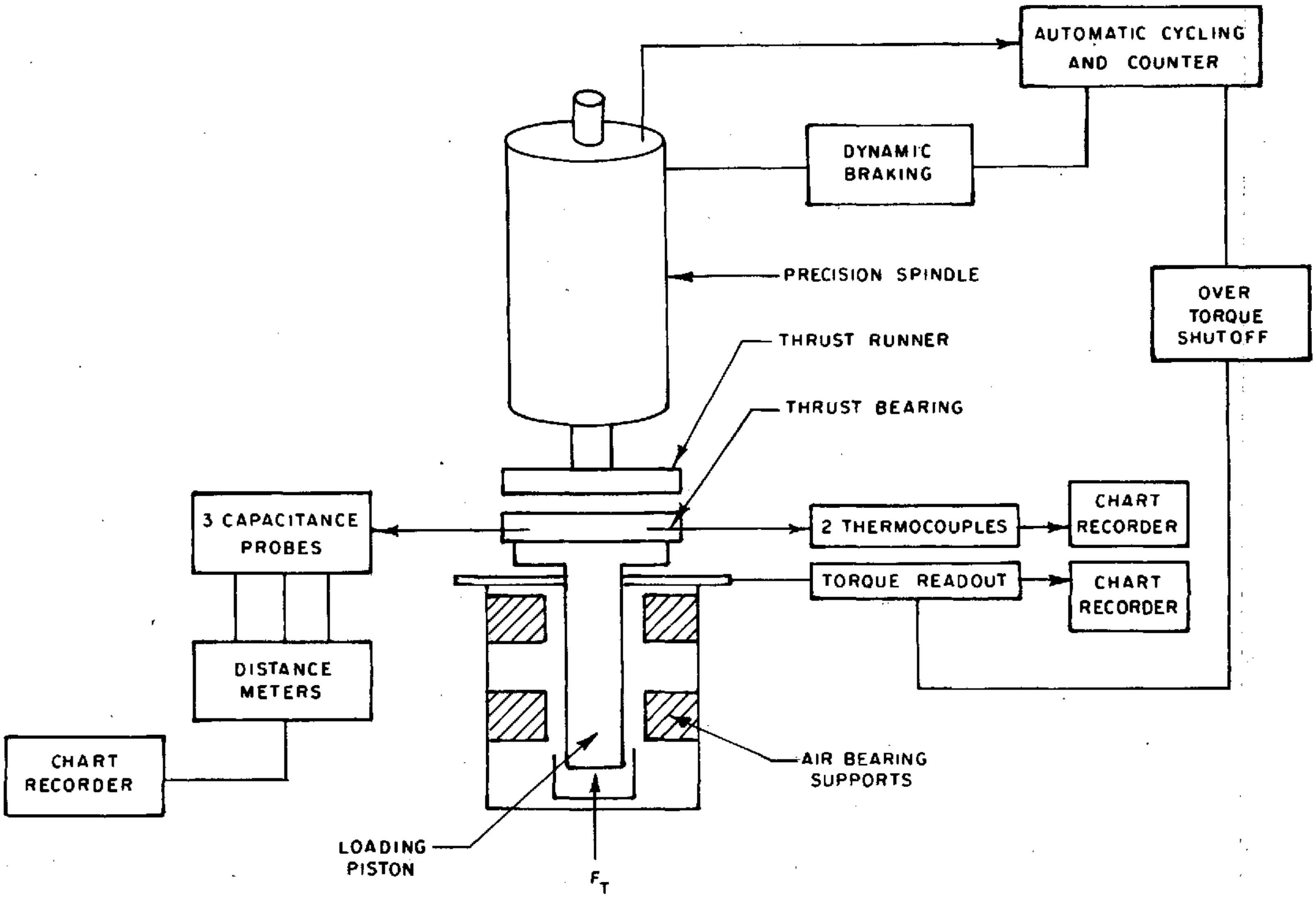

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Figure 5-2. Test Rig Schematic

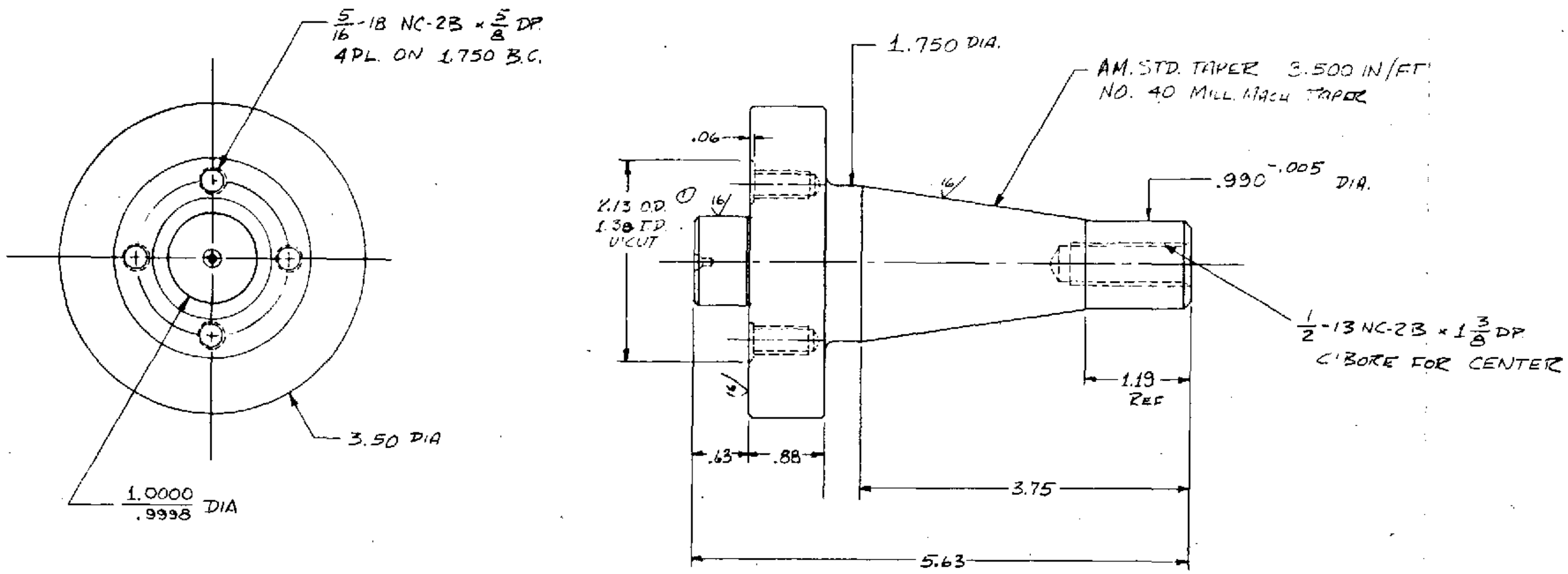

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Figure 5-3. Bearing Thrust Runner Arbor

restored for the next 15 second "on" cycle. Dynamic braking is applied at 16 seconds of the test cycle, just after the motor power is removed. Approximately 4.5 amperes DC is applied to one of the motor windings, giving the motor a retarding torque sufficient to stop the spindle within the 30 second off period. Automatic cycling to 1000 start-stop cycles, with two minute records at 15 minute intervals was accomplished. A sustained starting torque of approximately 10 times that normally recorded turned off all power and stopped the test.

It should be noted that accurate simulation of all conditions as encountered by the thrust bearing when used in the actual rotating machinery is very difficult. Time to lift off in the simulator (less than 1 second) is a function of the thrust bearing breakaway torque, motor bearing friction, system inertia, and the motor starting torque. After motor running torque is removed (at t + 15 seconds), time to touch down is a function of the thrust bearing torque (negligible before touch down), motor bearing friction (minimal) and the retarding torque applied by dynamic braking. Wear is a function of the time of contact only. The time of contact is substantially less than one second at start up, and approximately 4 to 5 seconds from touchdown to complete stop.

6. DETAILED TEST PROCEDURE

The following procedure for testing was followed:

a. Take average of three traverses across bearing and runner surfaces with Gould Surfanalyzer to obtain surface finish of surface.

b. Take average of three traverses perpendicular to bearing grooves to obtain groove depth.

c. Clean and degrease surfaces of bearing and runner with solvent (trichloroethylene).

d. Mount thrust bearing on subplate. Adjust alignment of bearing to spindle rotation by tightening elastic hinges. (Small perturbations are self-aligning.)

e. Mount thrust runner on spindle nose arbor. Successively tighten mounting bolts on arbor to adjust F.I.R. of thrust runner .0013 mm (50μin).

f. Check calibration of thrust load cell at load desired before starting test. Calibrate torque system.

g. Warm up Brush 6-channel recorder. Turn on temperature recorder.

h. Again degrease bearing surfaces.

i. Adjust thrust on bearing to load desired.

j. Take zero reading on three capacitance distance probes. Adjust bias on Brush recorder so that output reads zero distance on bearing clearance channels. Set torque channel to read zero when bearing is stationary.

k. Start automatic operation of test machine. Spindle motor power to be on 15 seconds, 30 seconds off. Adjust coast down time (to complete stop) to 25 to 29 seconds by varying dynamic braking current applied.

l. After 1000 cycles are completed, visually check bearing and runner for wear. When required remove test samples, photograph and surface finish test.

m. Remount specimens and repeat procedure until 15,000 cycles or failure occurs.

7. PHOTOGRAPHIC AND INSPECTION RECORDS OF THE TEST PARTS

7.1 CHROME OXIDE COATED BEARING - 44N (10 lbf) LOAD (BEARING SET#5), TEST 1A

7.2 CHROME OXIDE COATED BEARING - 156N (35 lbf) LOAD (BEARING SET #3). TEST 1B

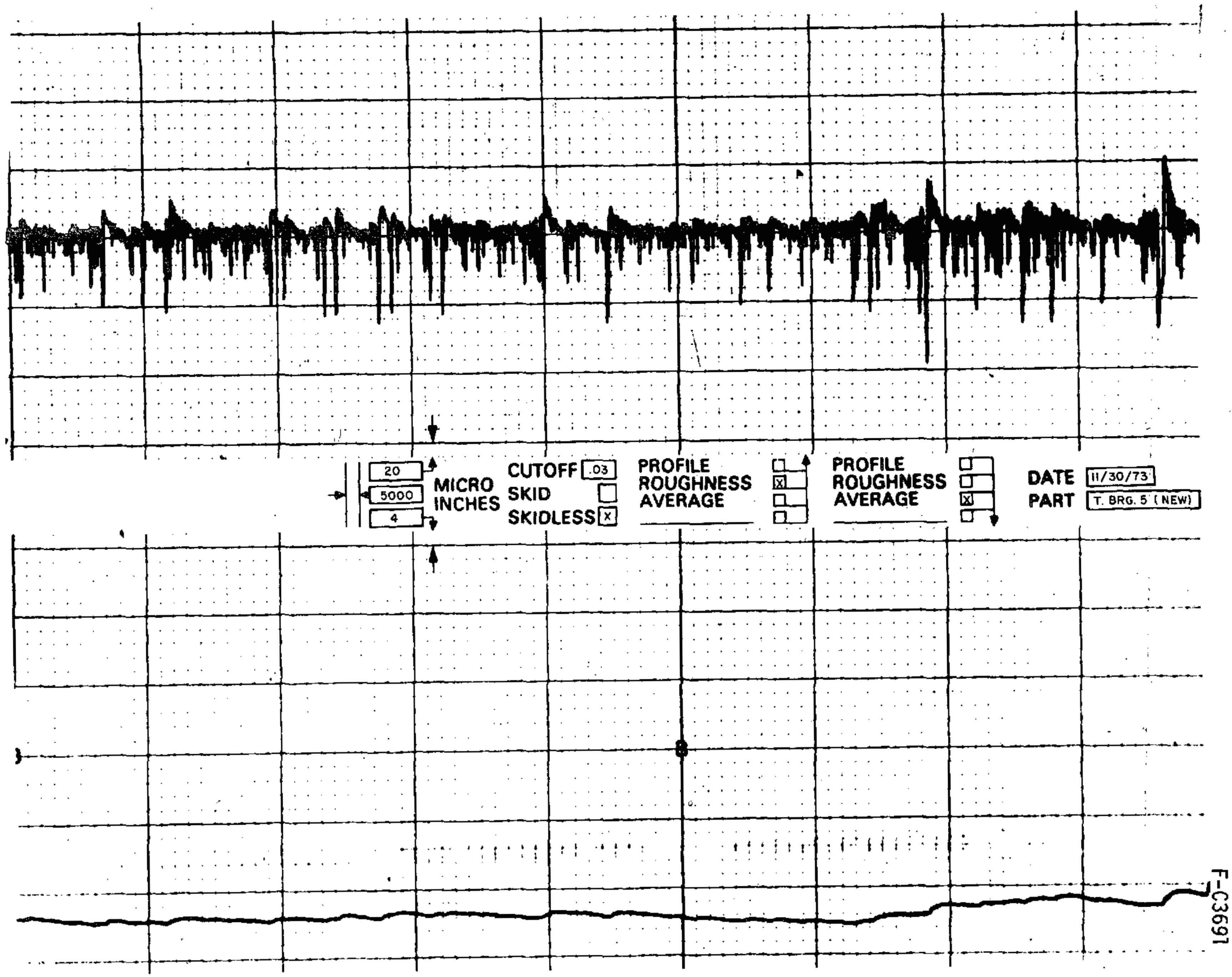

Figure 7-1. Surface Finish Thrust Runner #5, (New)

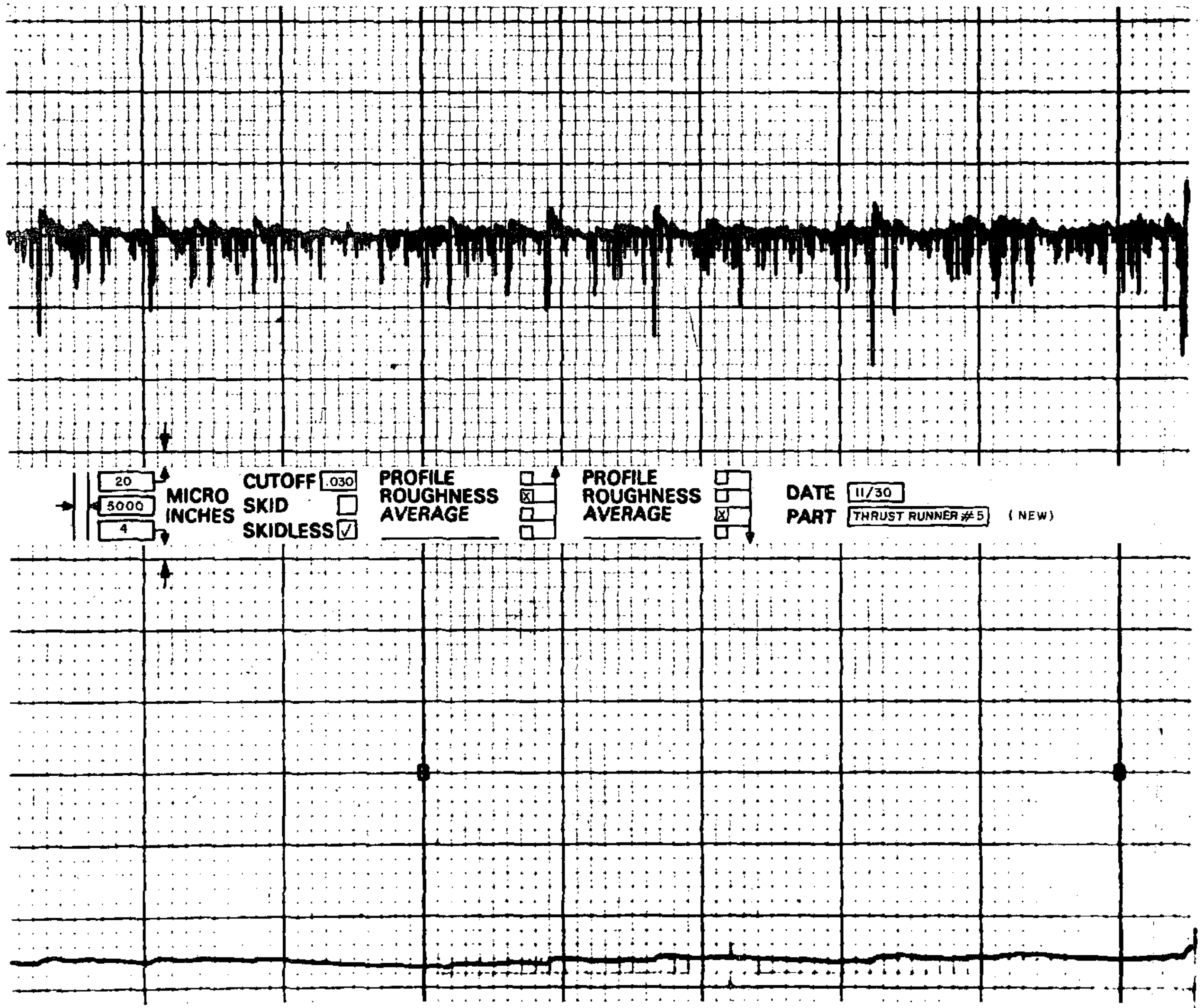

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Figure 7-2. Surface Finish Thrust Bearing #5 (New)

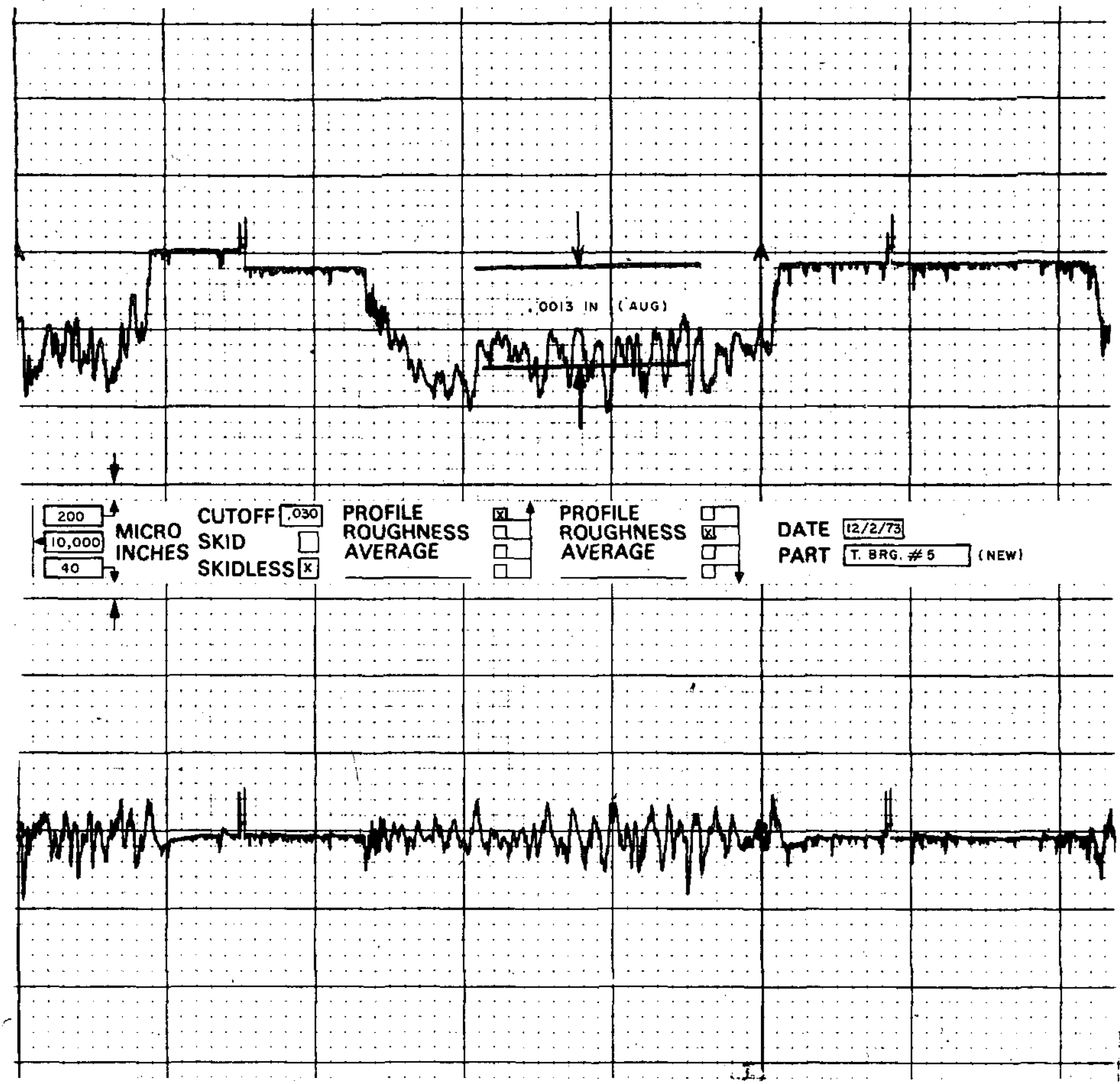

Figure 7-3. Groove Depth, Thrust Bearing #5

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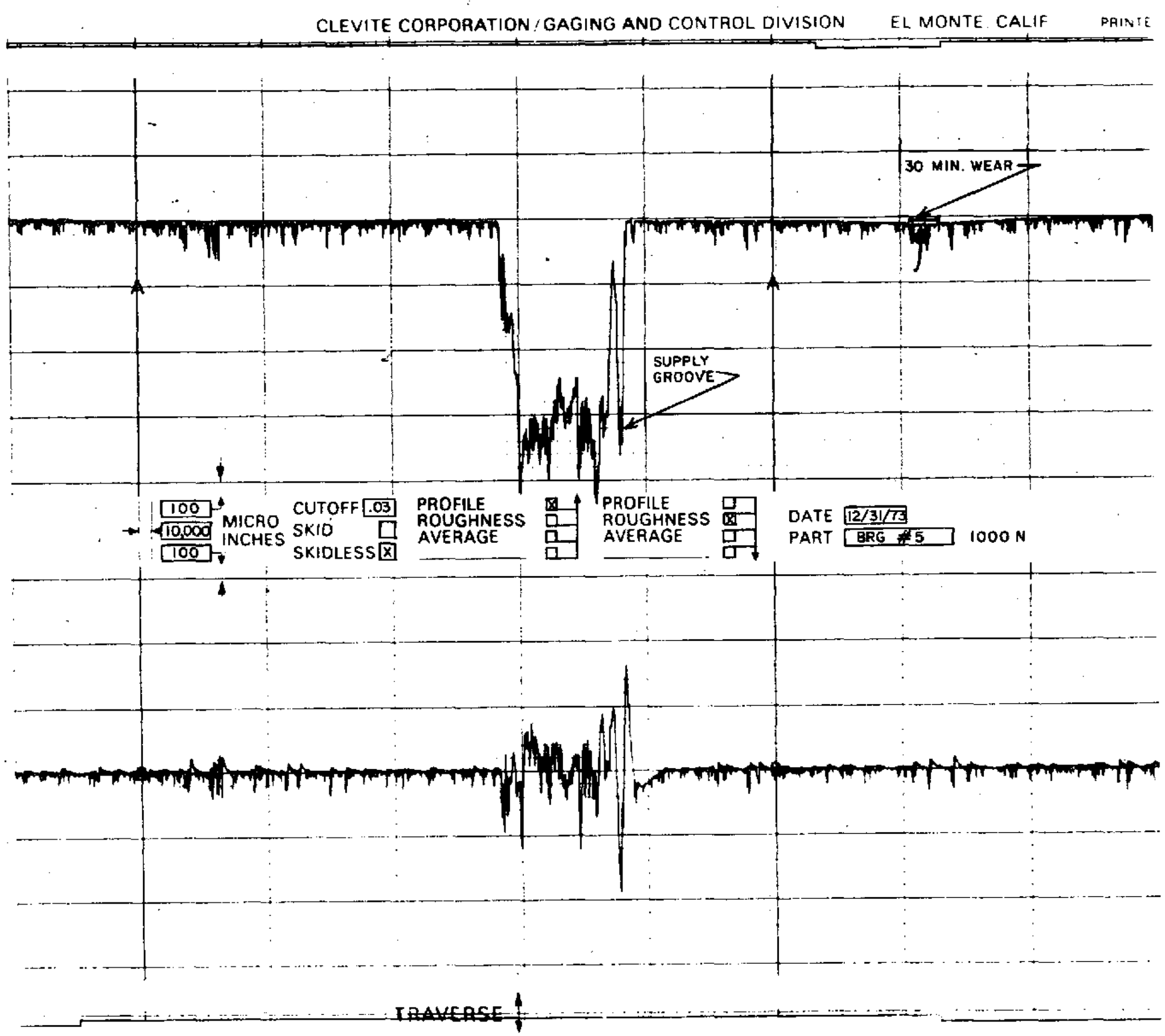

Figure 7-4. Bearing No. 5, Surface Contour, 1000 Cycles, 44N (10 lbf) Load

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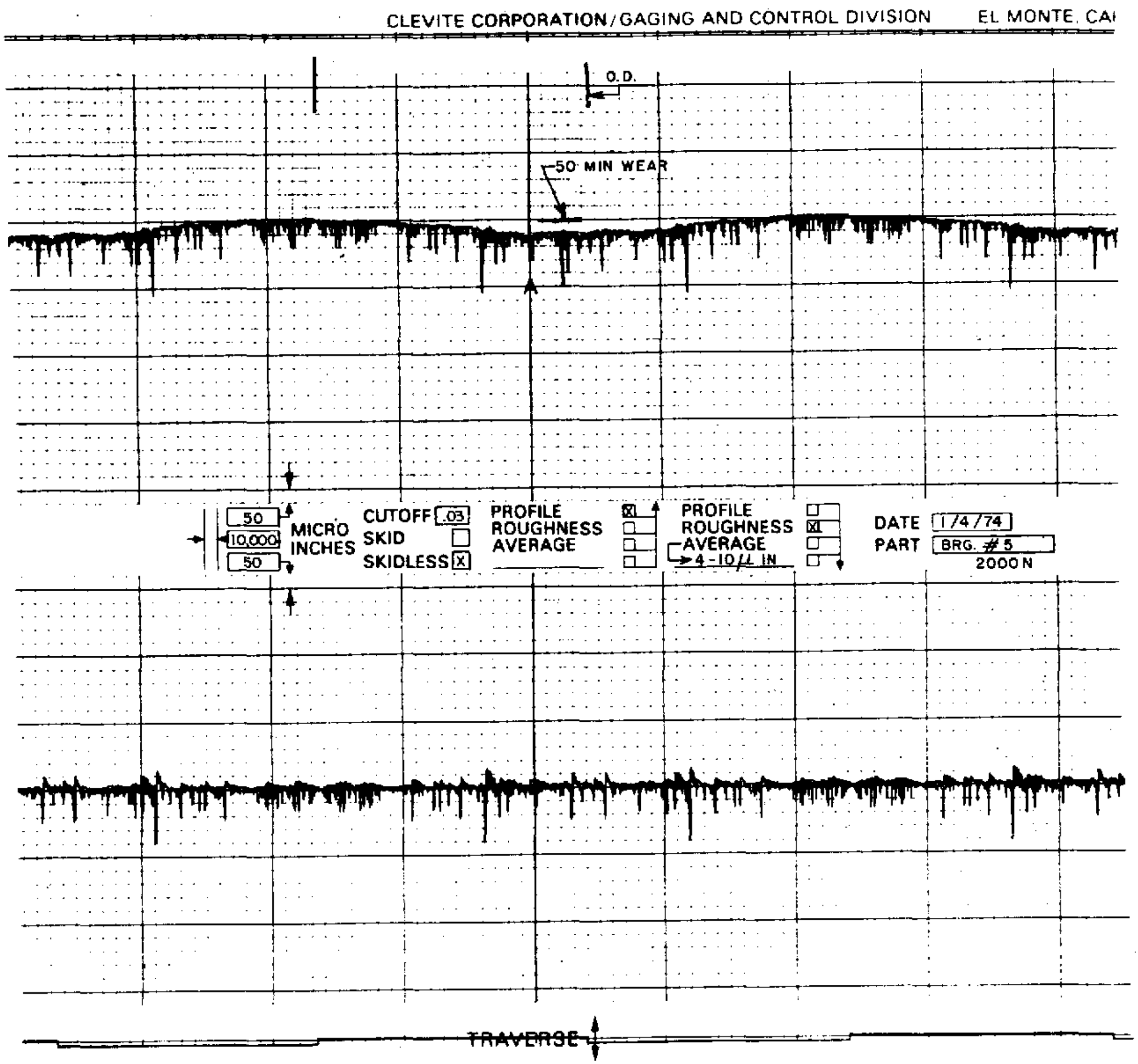

Figure 7-5. Bearing No. 5, Surface Contour, 2000 Cycles, 44N (10 lbf) Load

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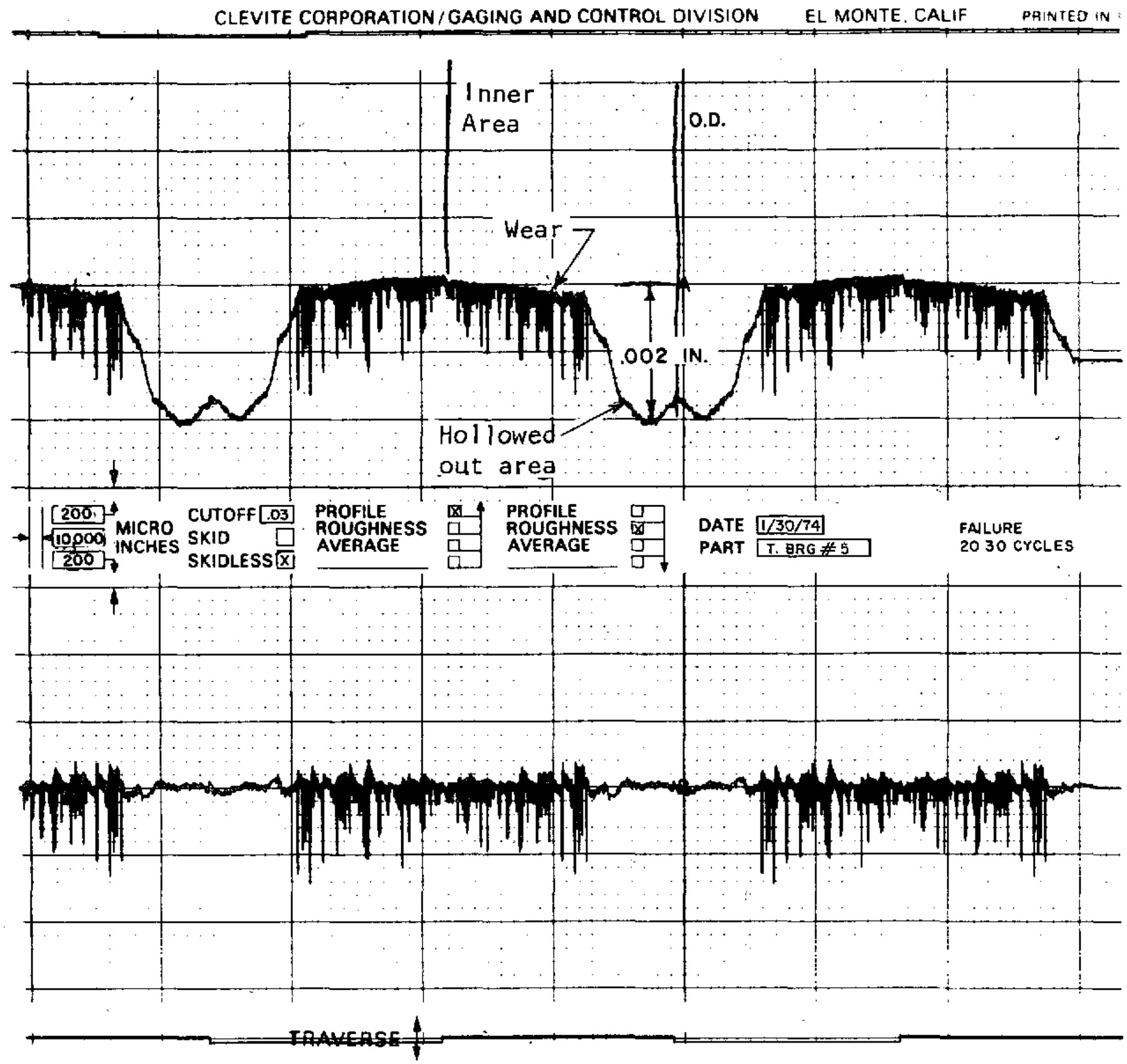

Figure 7-6. Bearing No. 5, Surface Contour, 2030 Cycles, 44N (10 lbf) Load, Failure

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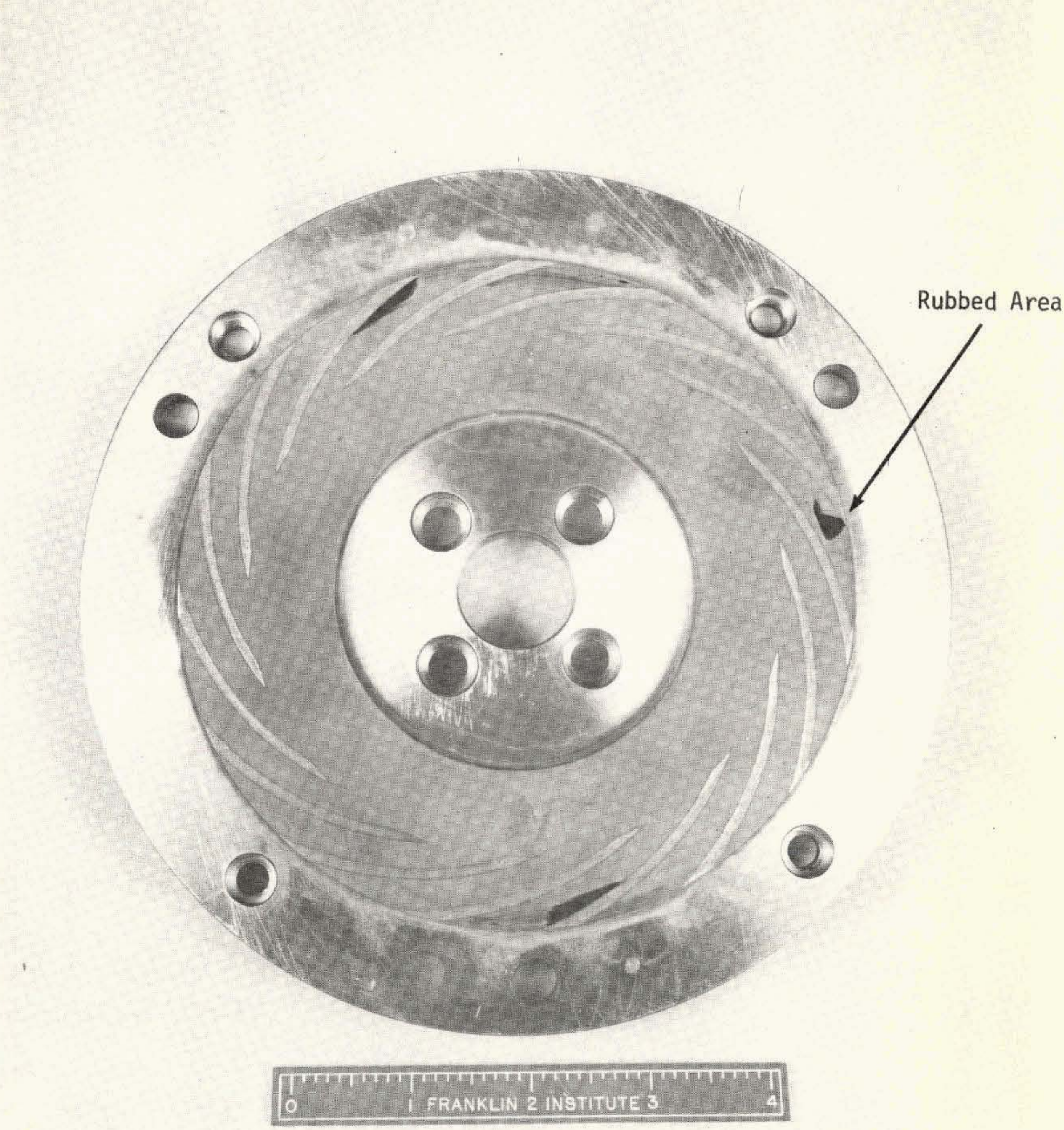

Figure 7-7. Thrust Bearing No. 5 Failure at 2030 Cycles

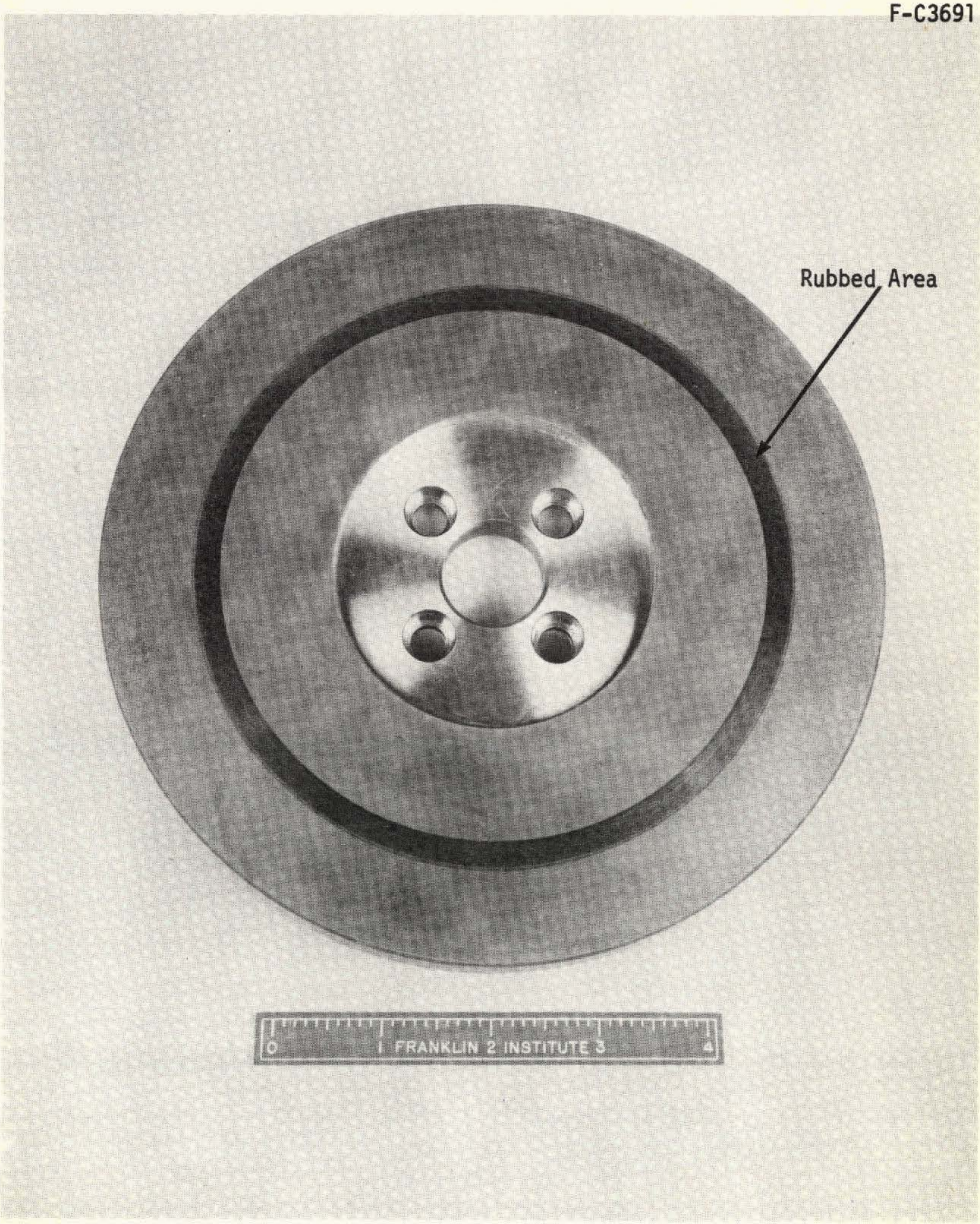

Figure 7-8. Thrust Runner No. 5, Failure at 2030 Cycles

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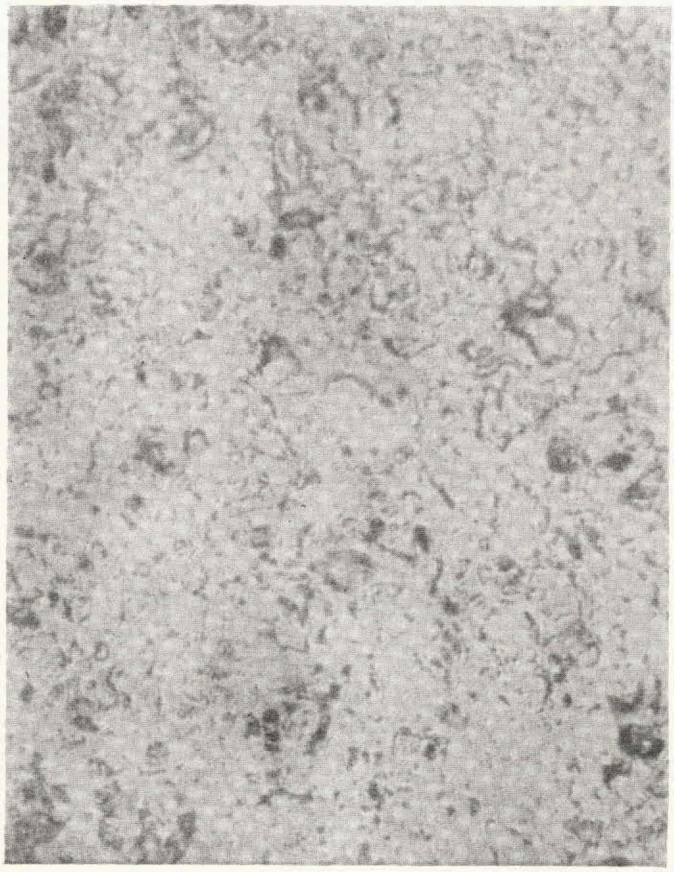

Figure 7-9A. Microphoto of Bearing No. 5, Virgin Surface, 250X

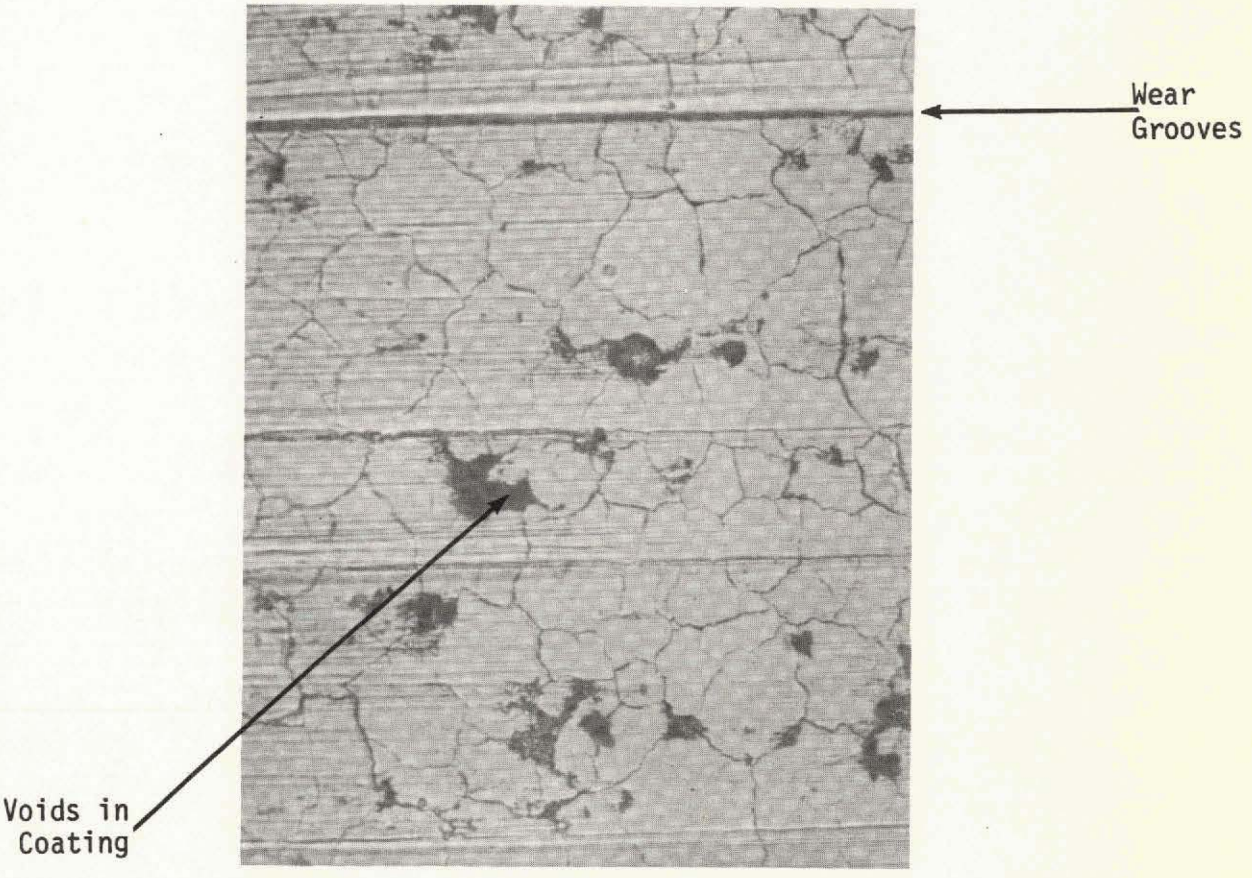

Figure 7-9B. Microphoto of Bearing No. 5 at Failure: 250X

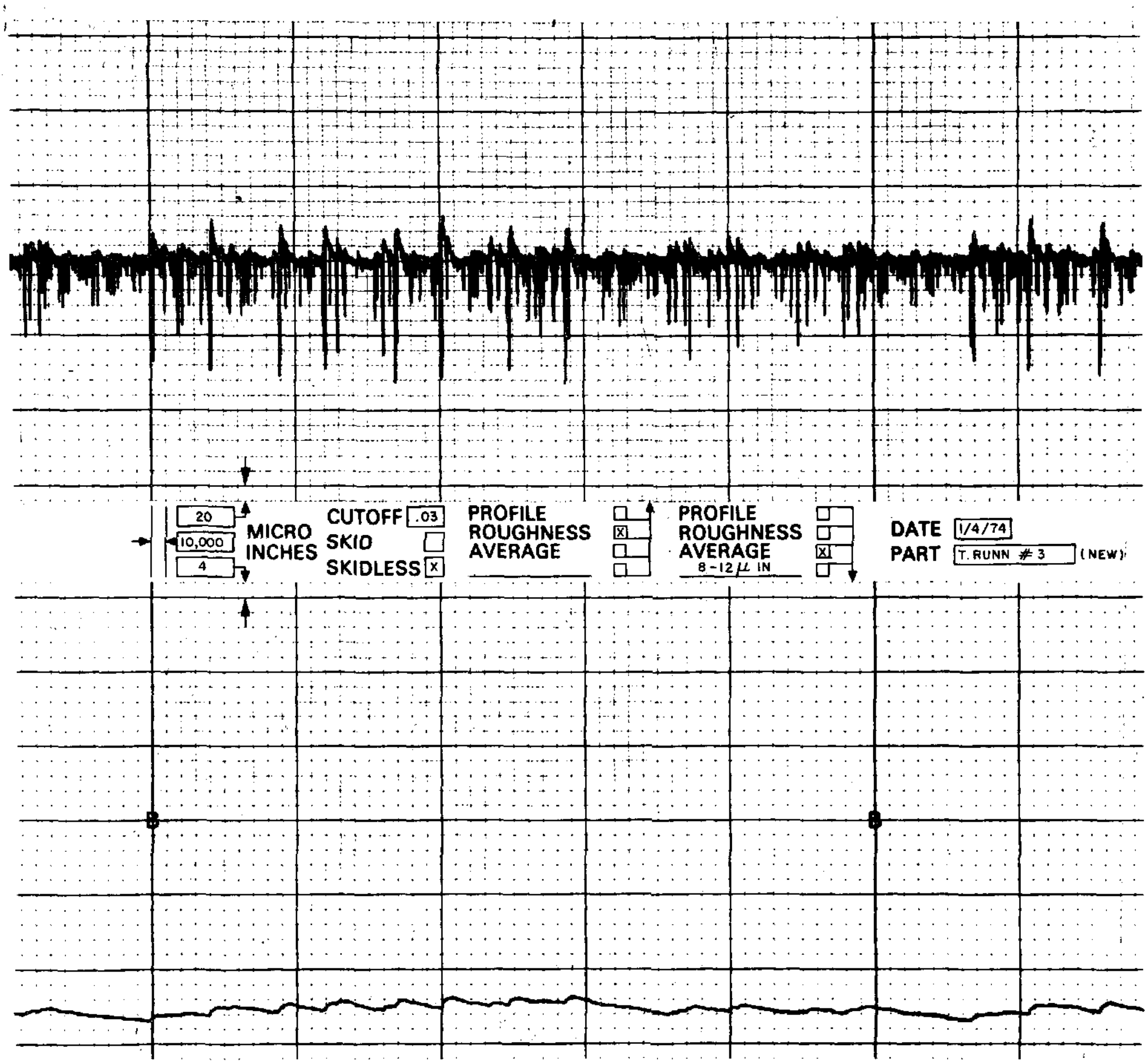

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Figure 7-10. Surface Finish, Thrust Runner #3 (New)

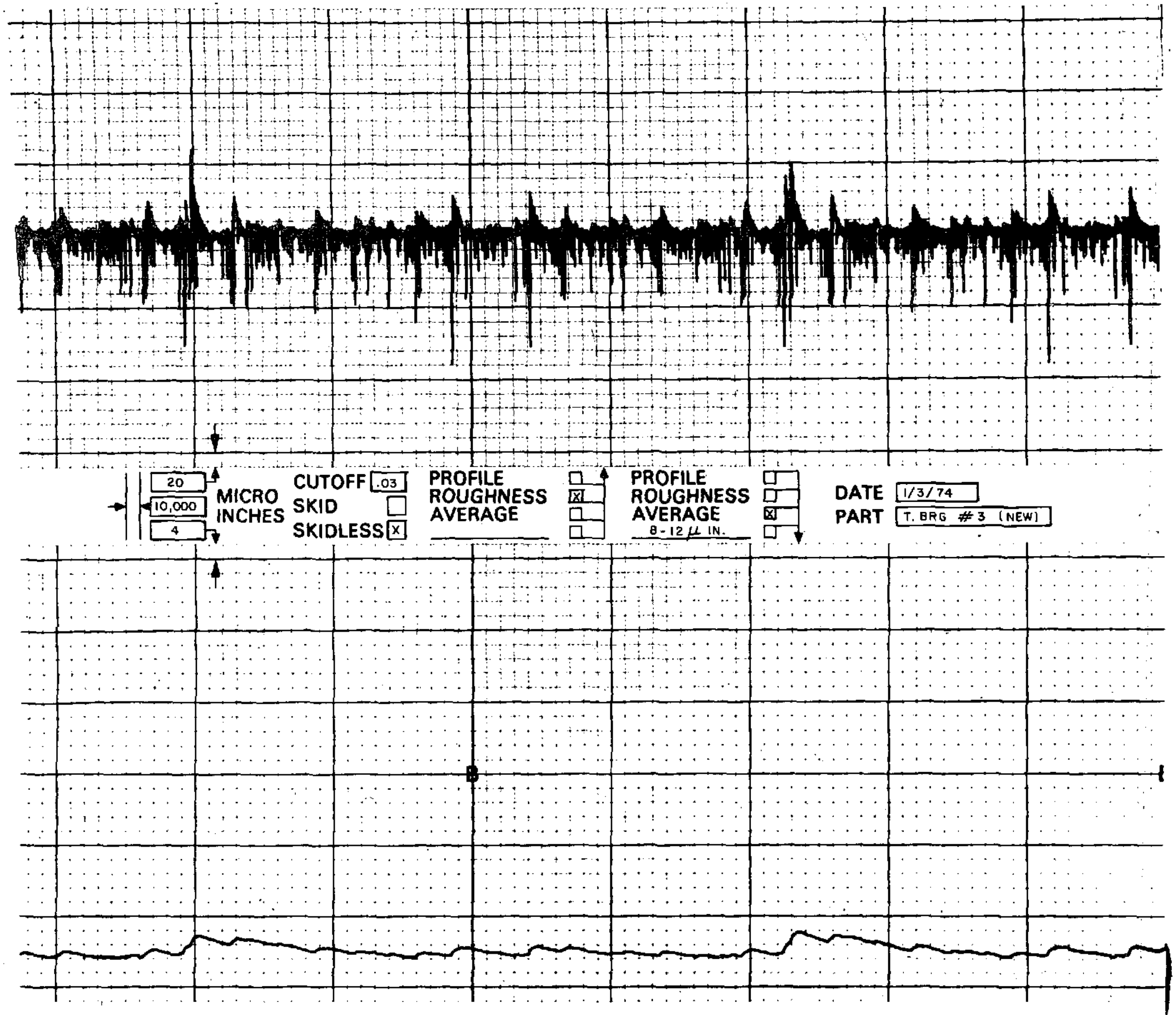

Figure 7-11. Surface Finish, Thrust Bearing #3 (New)

F-C3691

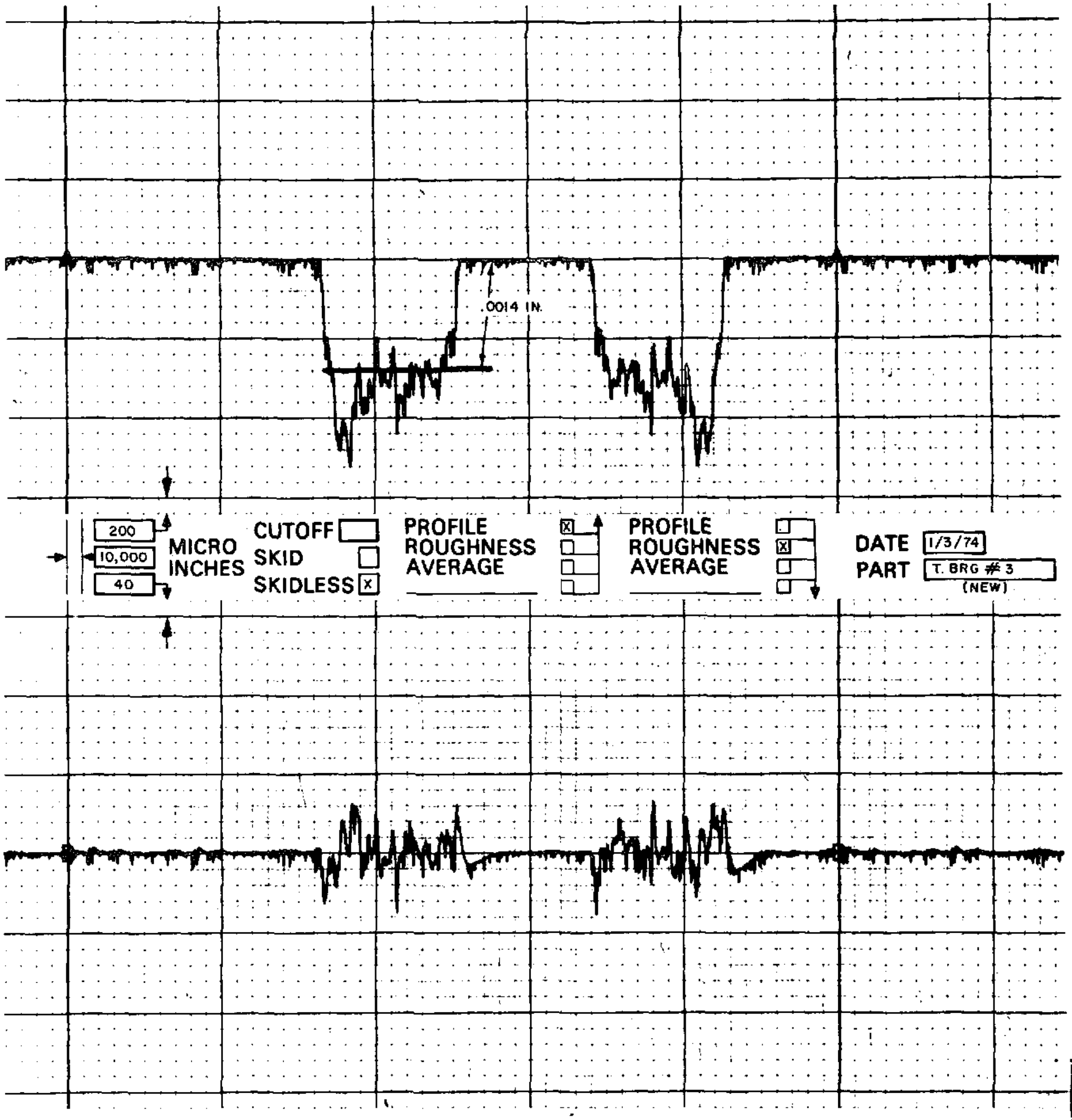

Figure 7-12. Groove Depth, Thrust Bearing #3

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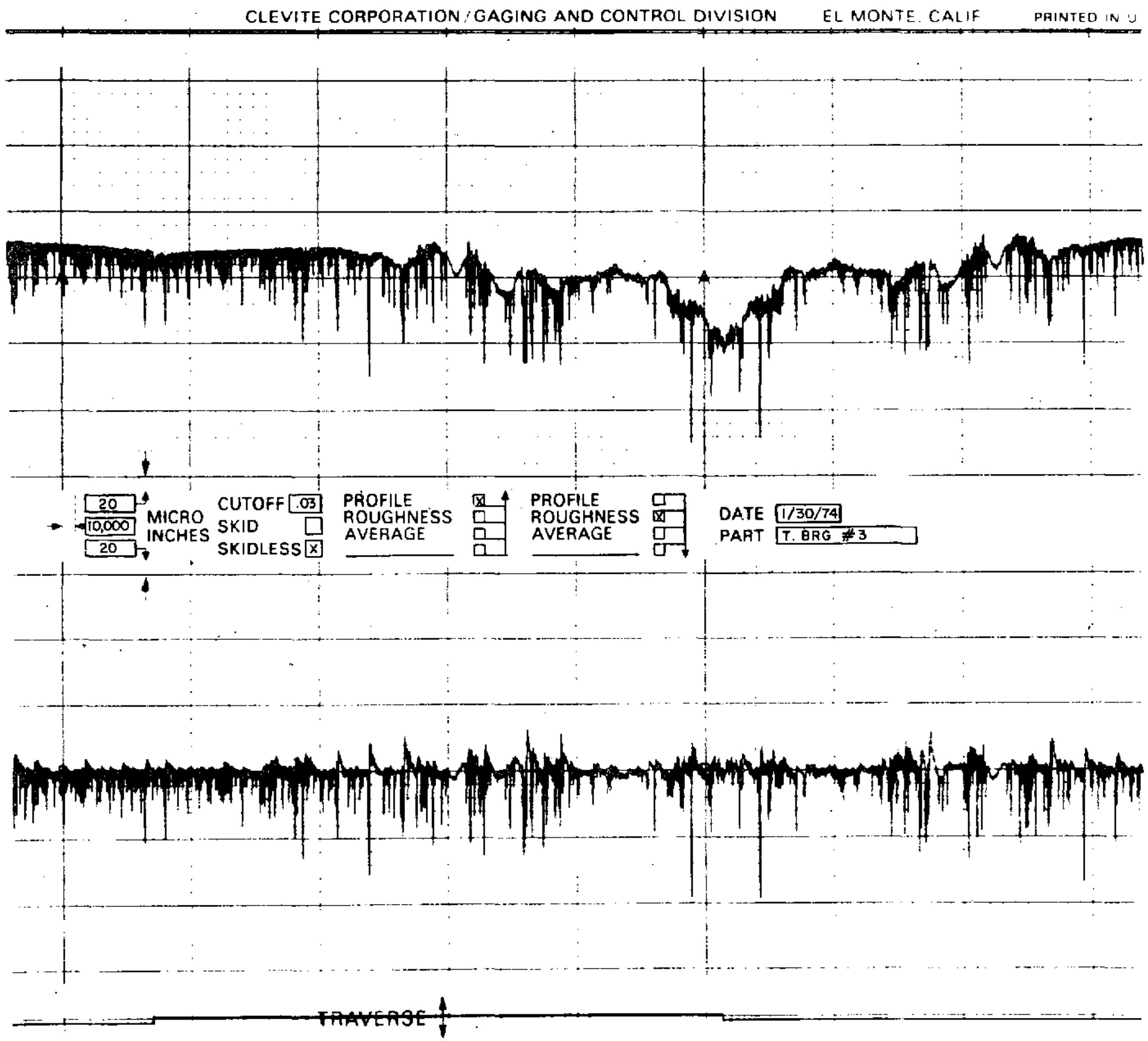

Figure 7-13. Bearing No. 3, Surface Contour, 35 Cycles, 156N (35 lbf) Load, Failure

F-C3691

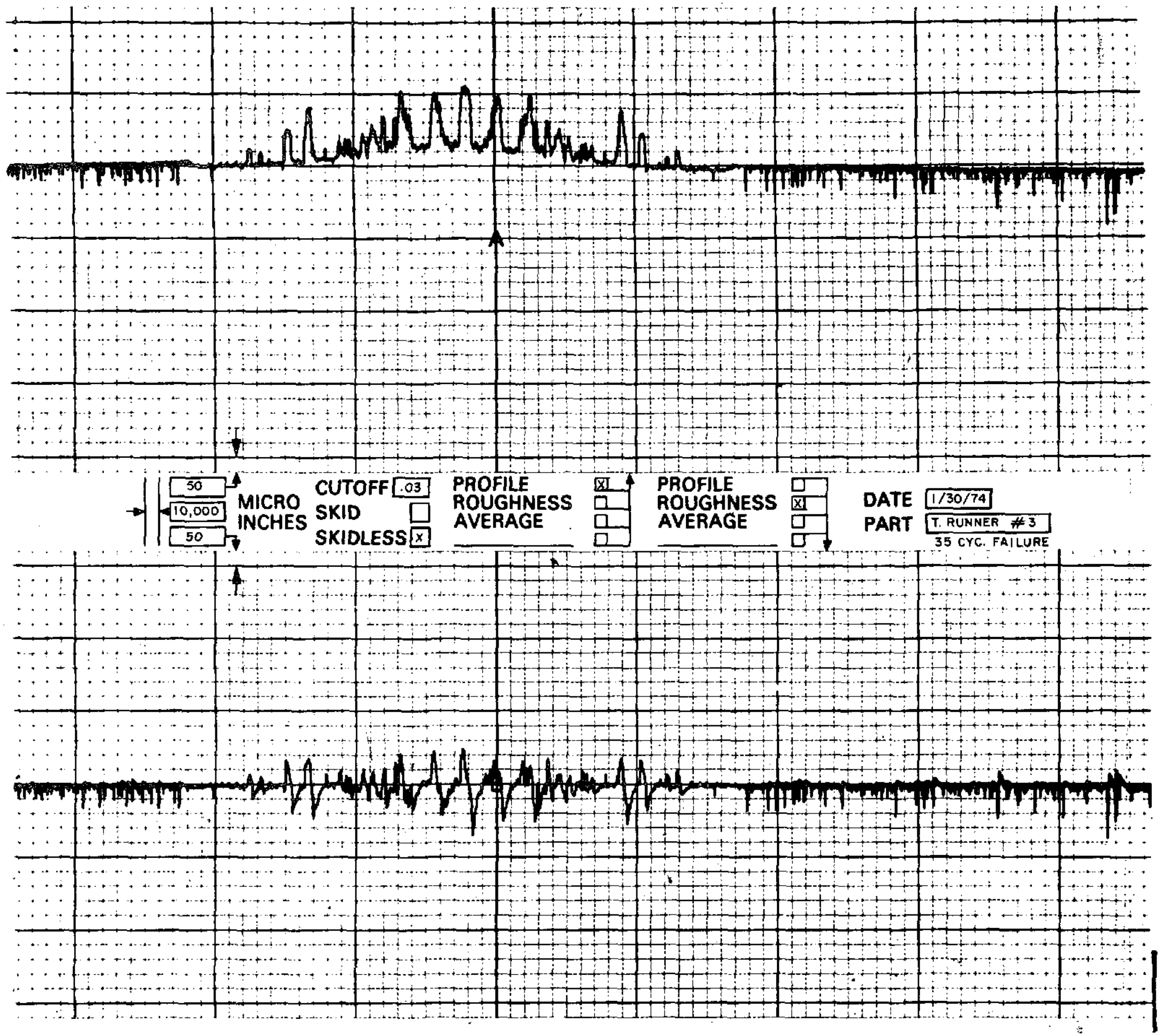

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Figure 7-14. Thrust Runner #3, Surface Contour, 35 Cycles, 156N (35 lbf) Load, Failure

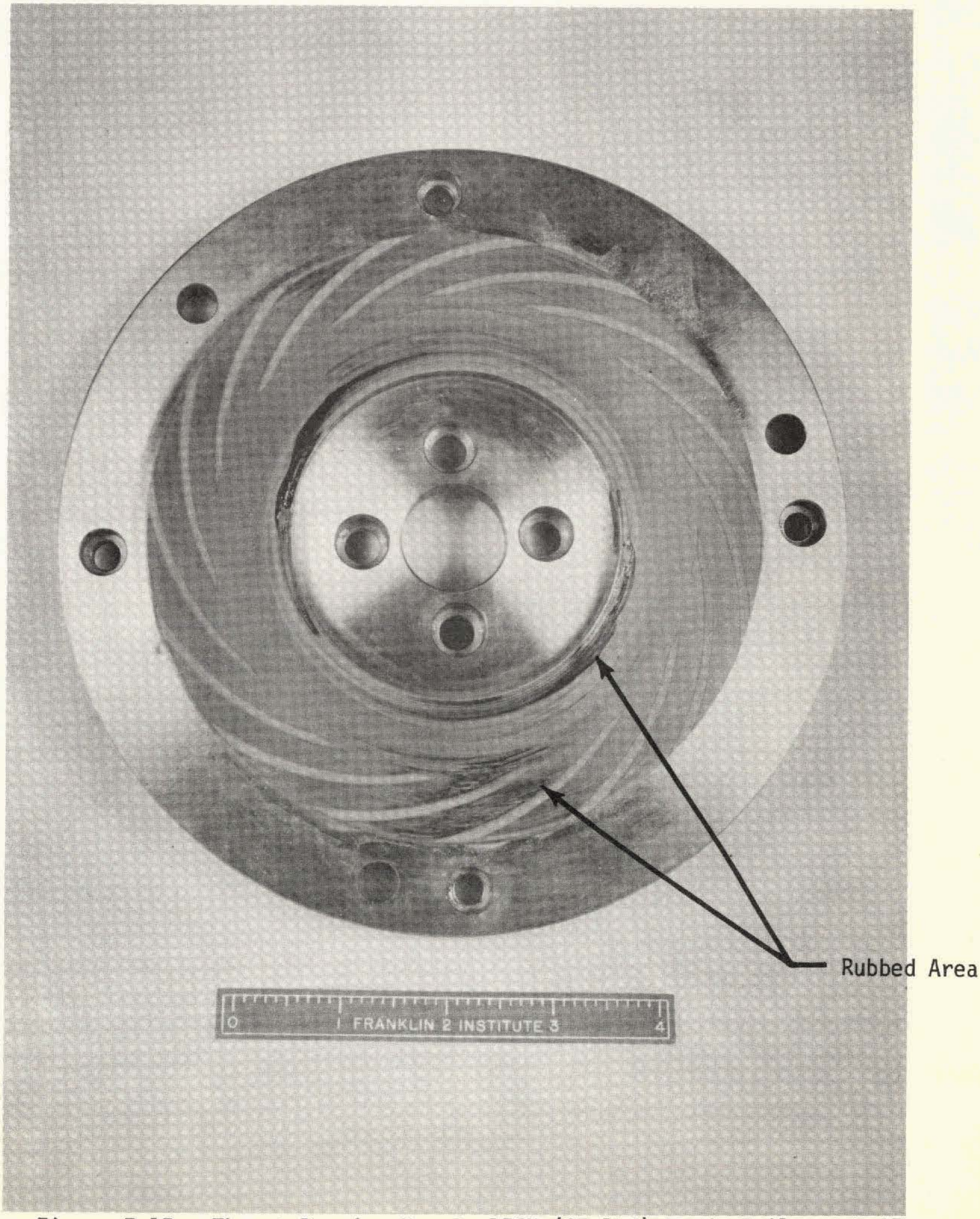

Figure 7-15. Thrust Bearing No. 3, 156N (35 lbf) Load, Failure at 35 Cycles

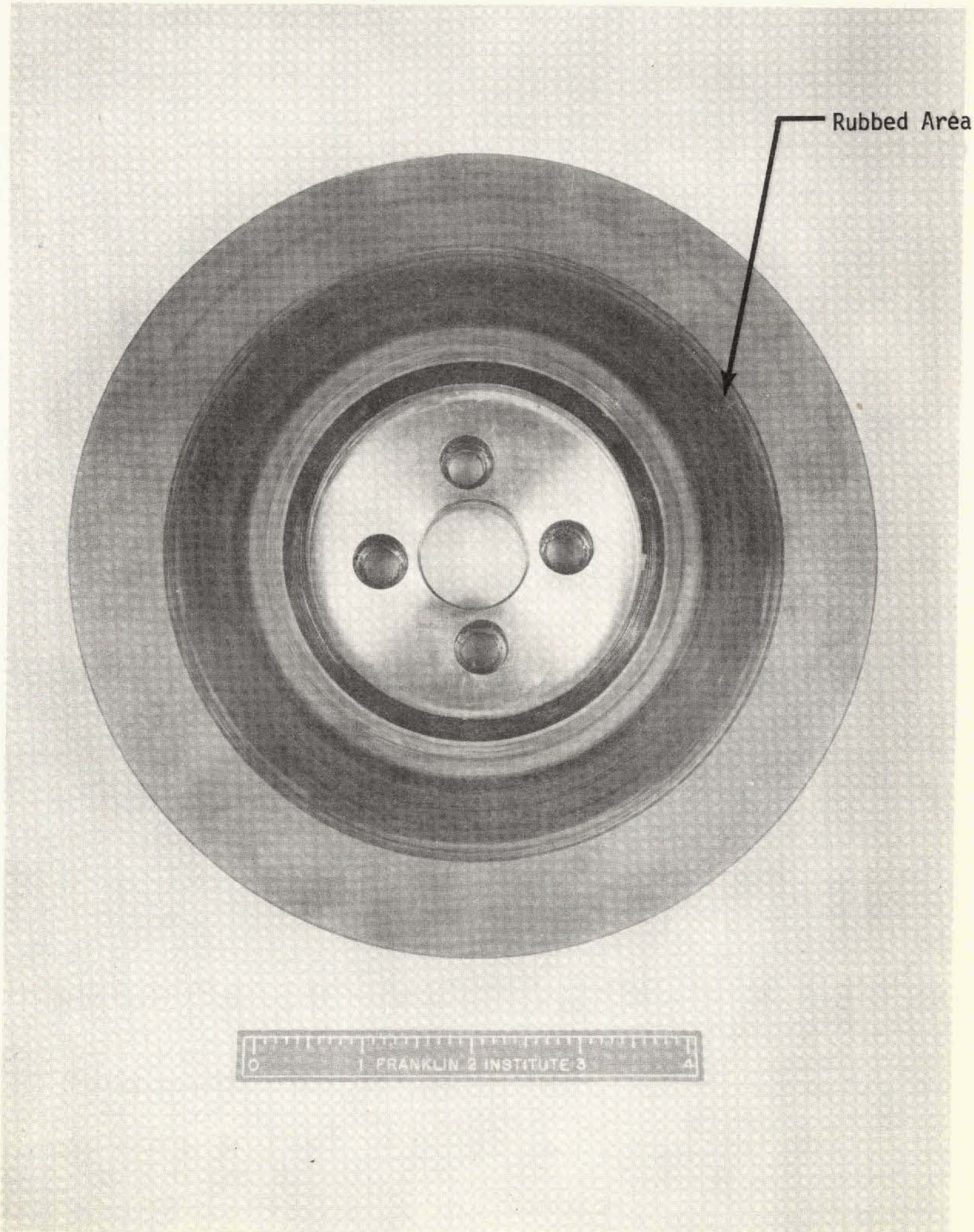

Figure 7-16. Thrust Bearing No. 3, 156N (35 lbf) Load, Failure at 35 Cycles

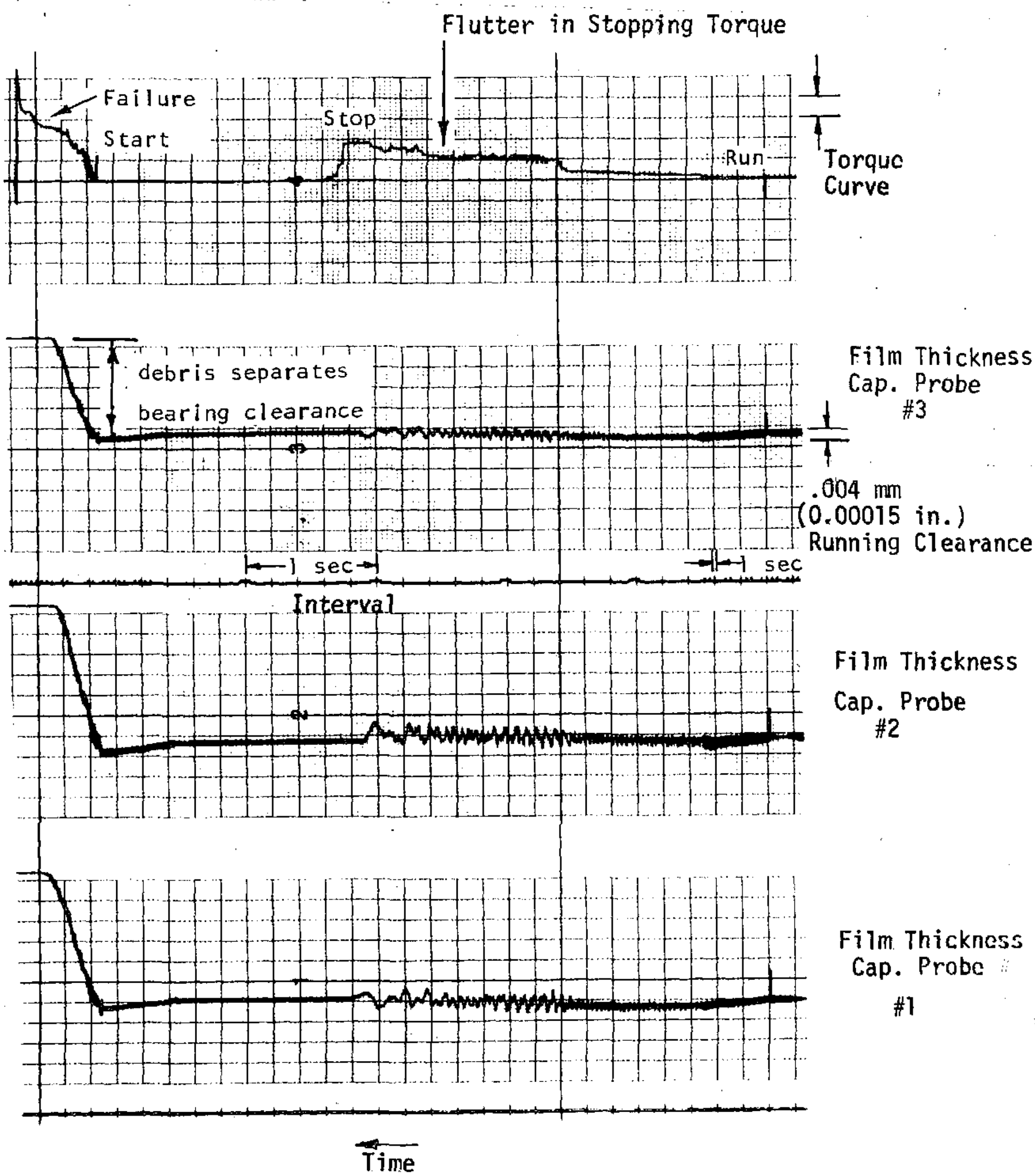

Figure 7-17. Portion of Bearing Clearance vs. Torque Curves, Bearing Set No. 3 at 35 Cycles, 156 (35 lbf) Load, Failure

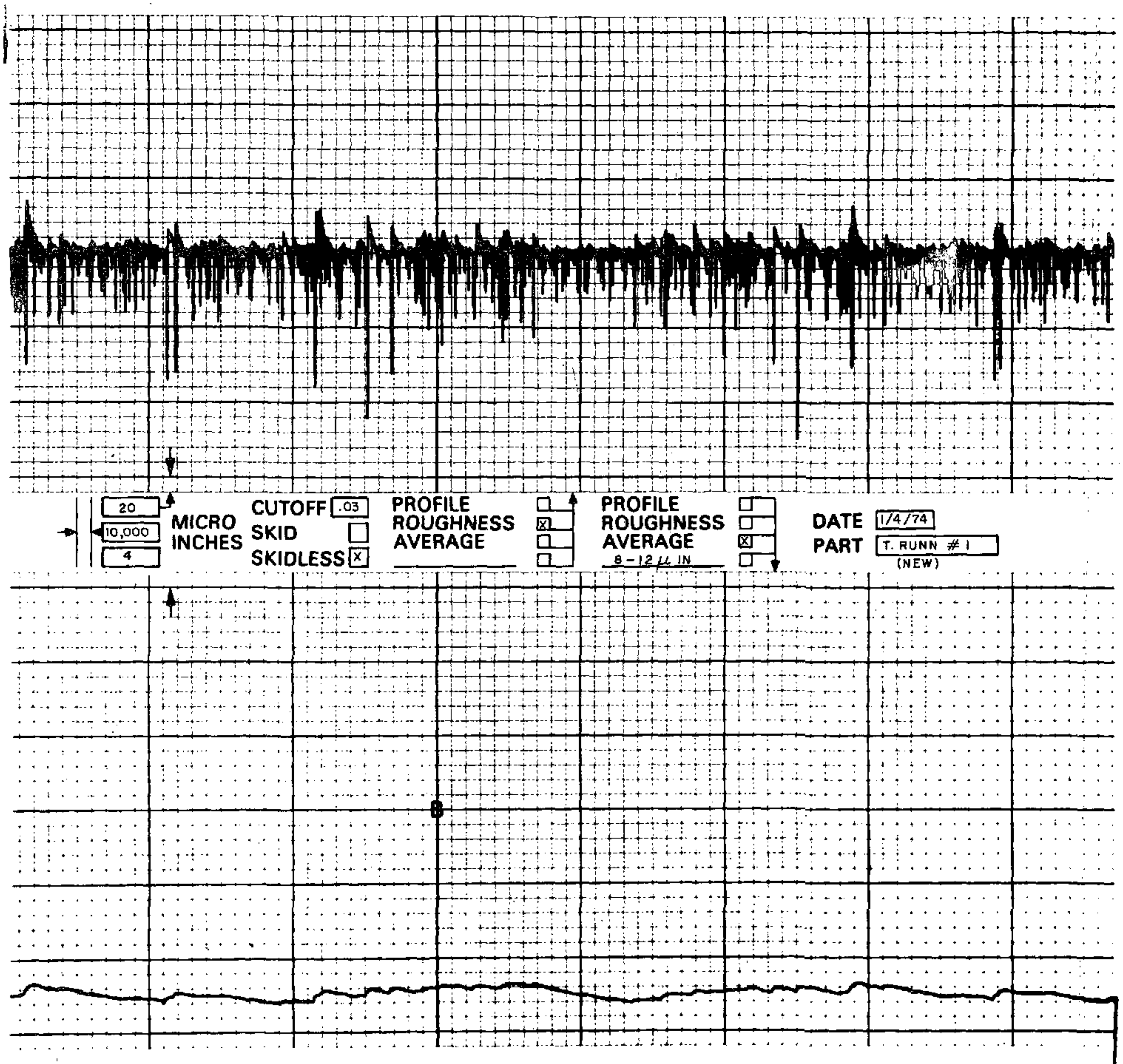

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Figure 7-18. Surface Finish, Thrust Runner #1 (New) before MoS_2 Coating

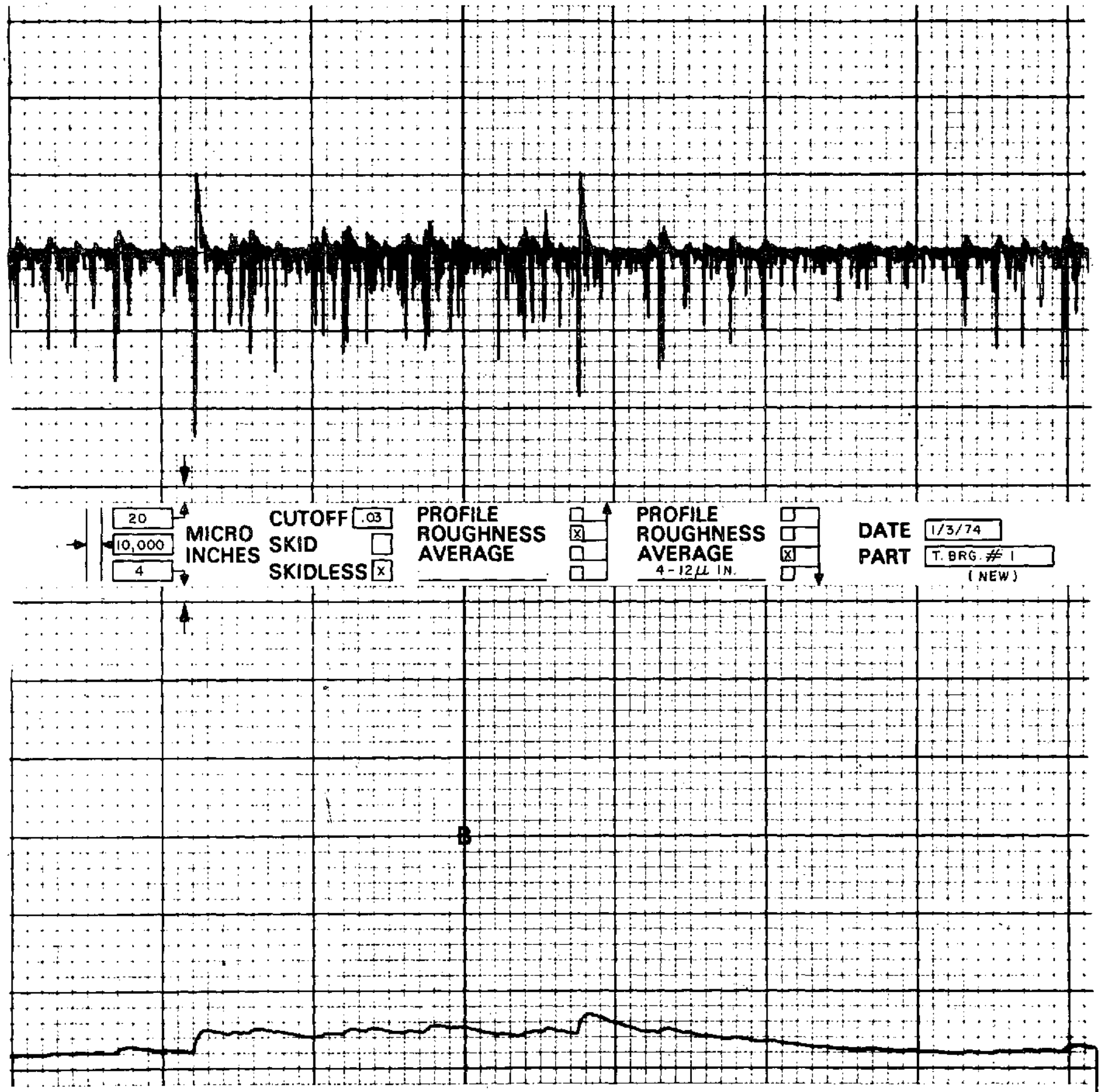

Figure 7-19. Surface Finish, Thrust Bearing #1 (New) Before MoS_2 Coating

F-C3691

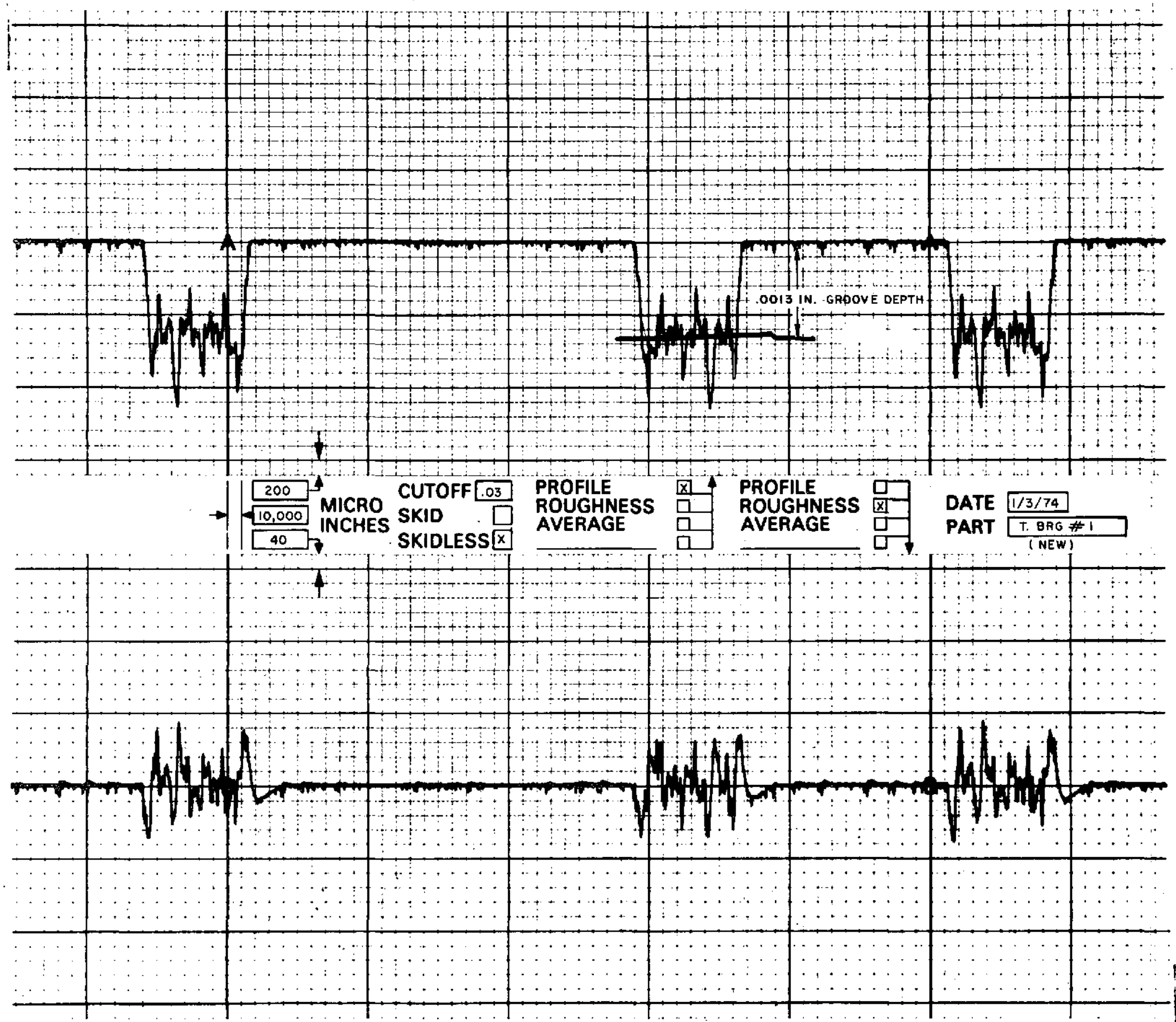

Figure 7-20. Groove Depth, Thrust Bearing #1 Before MoS_2 Coating

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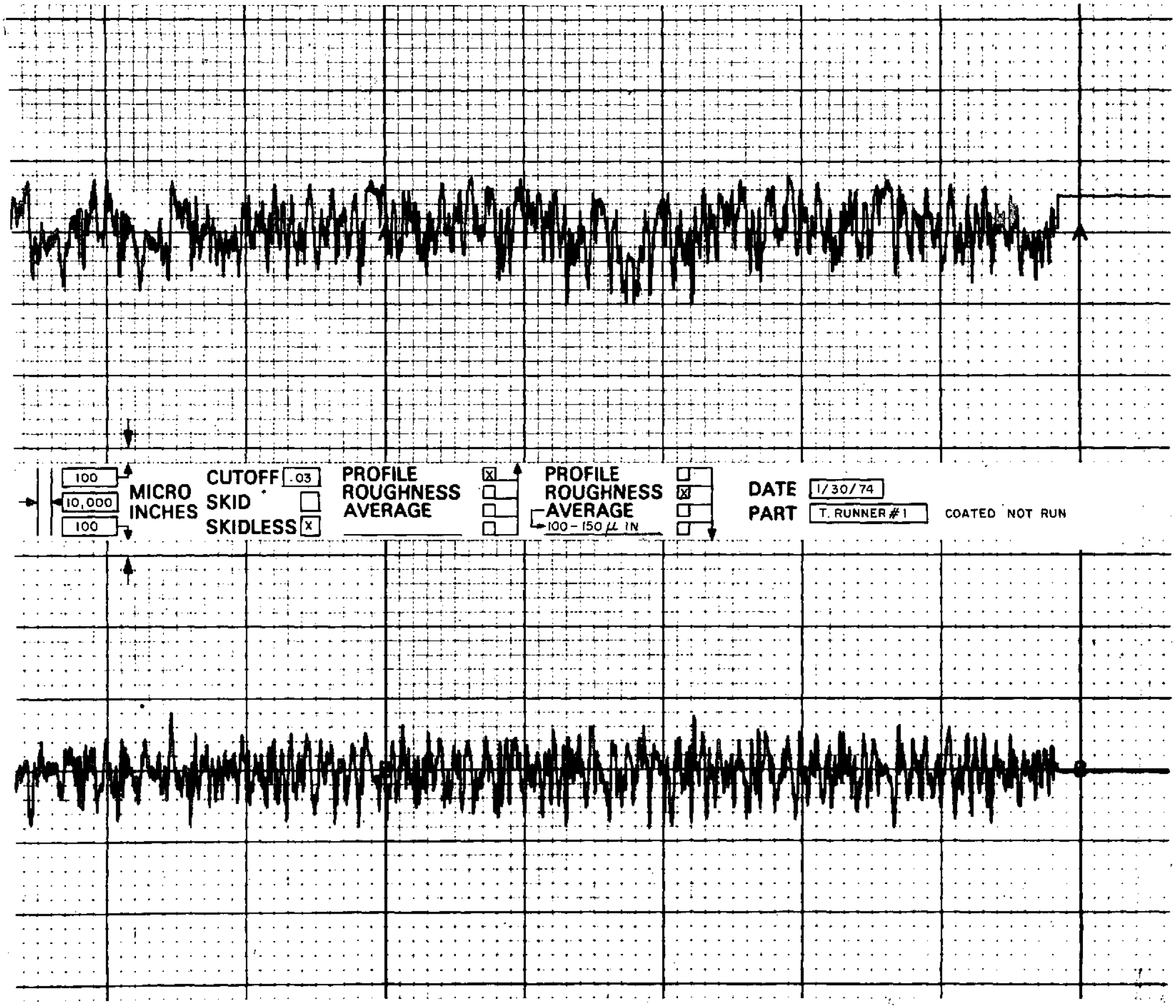

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Figure 7-21. Surface Finish, Thrust Runner #1, as Received After MoS_2 Coating

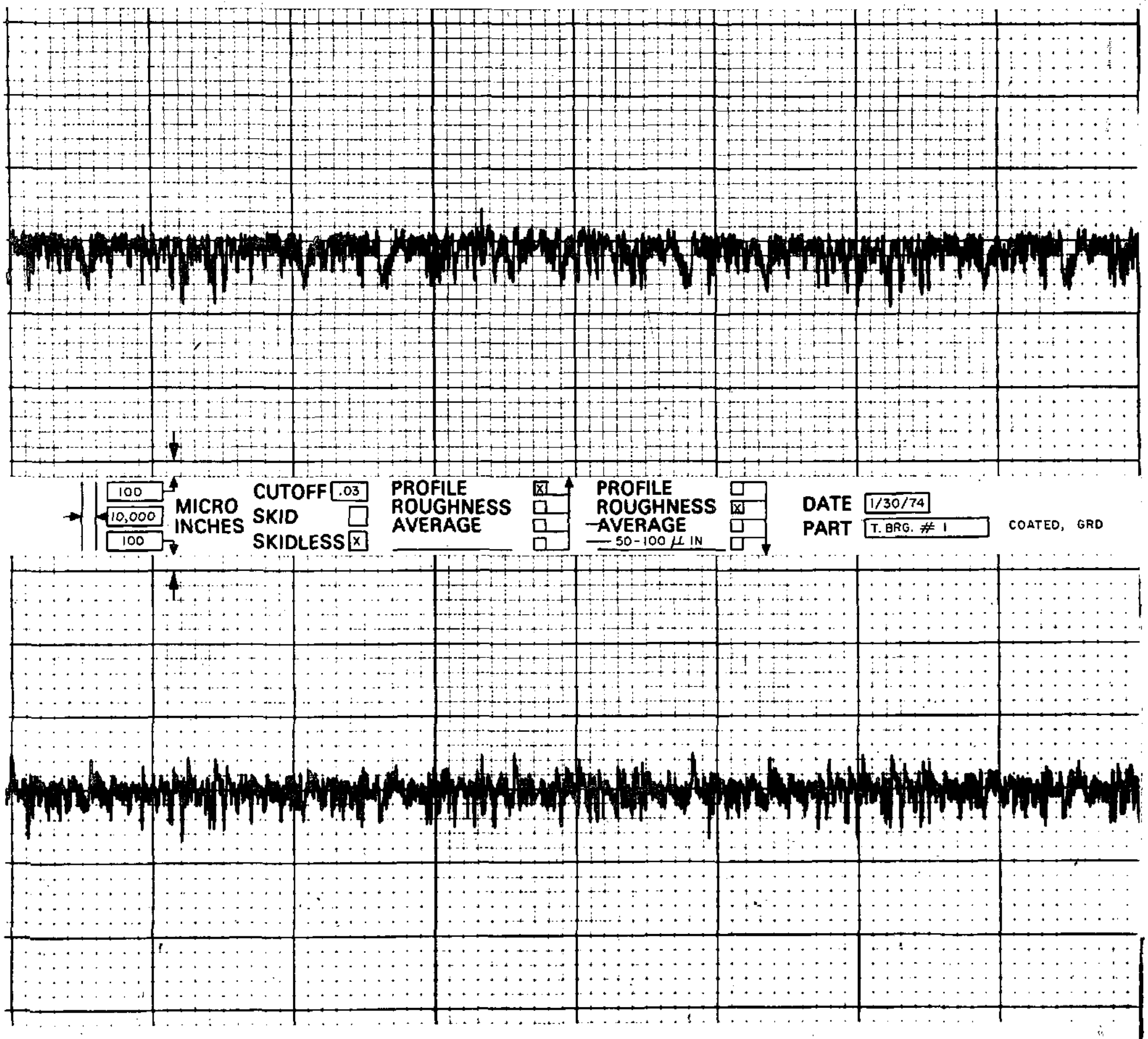

Figure 7-22. Surface Finish, Thrust Runner #1, After Grinding MoS_2 Coating to Required Coating Thickness

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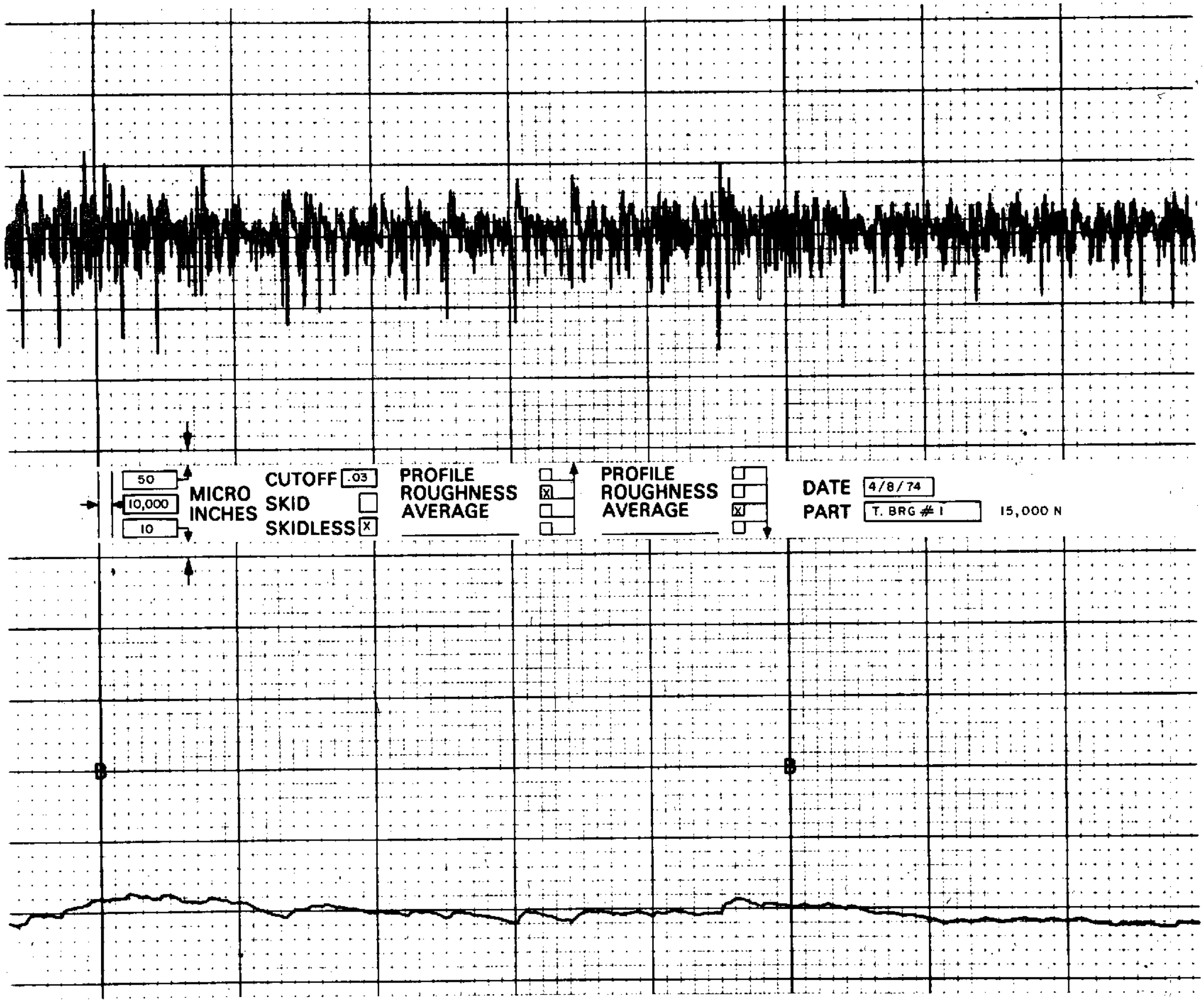

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Figure 7-23. Thrust Bearing No. 1, Surface Contour After 15,000 Start-Stop Cycles

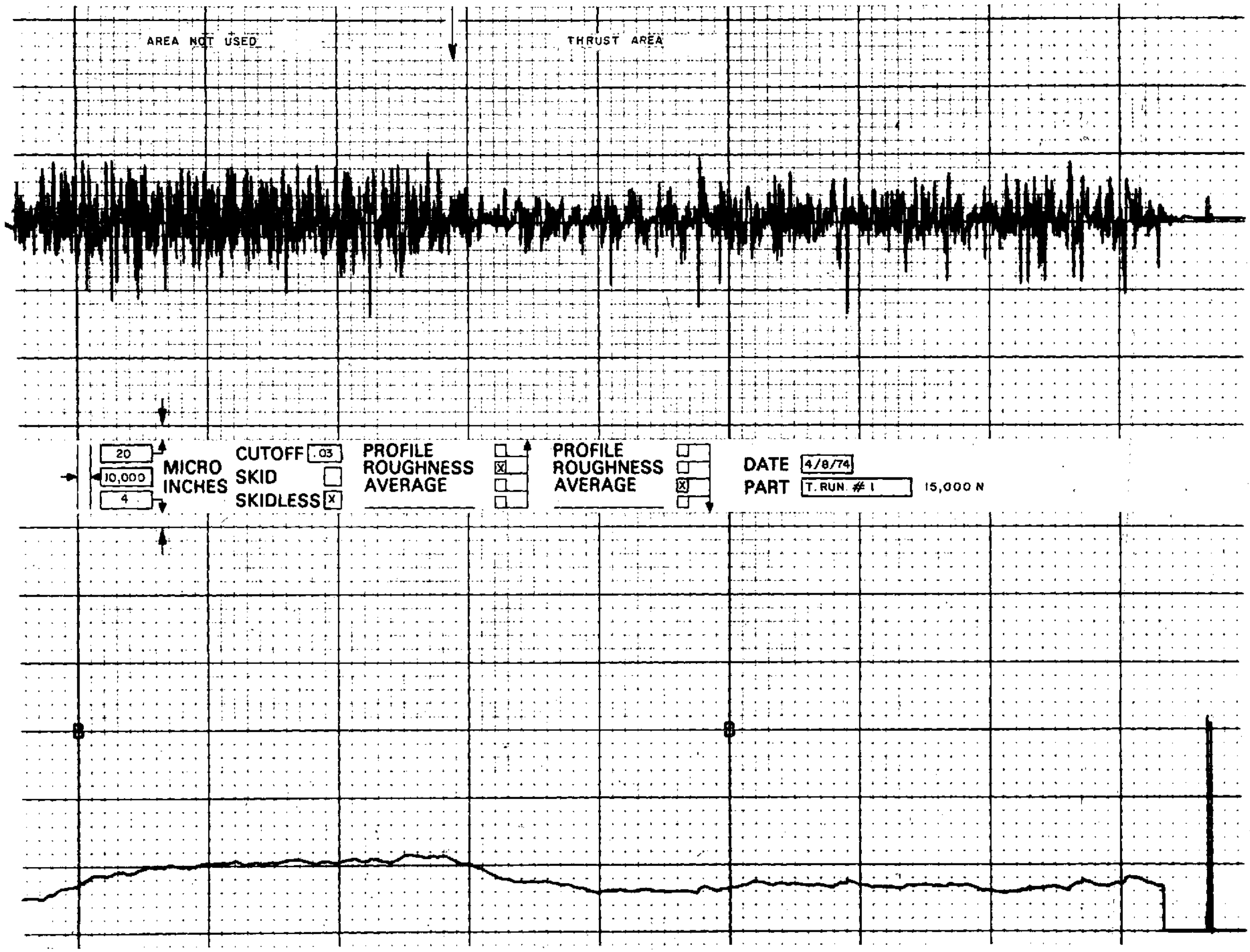

Figure 7-24. Thrust Runner No. 1, Surface Contour After 15,000 Start-Stop Cycles

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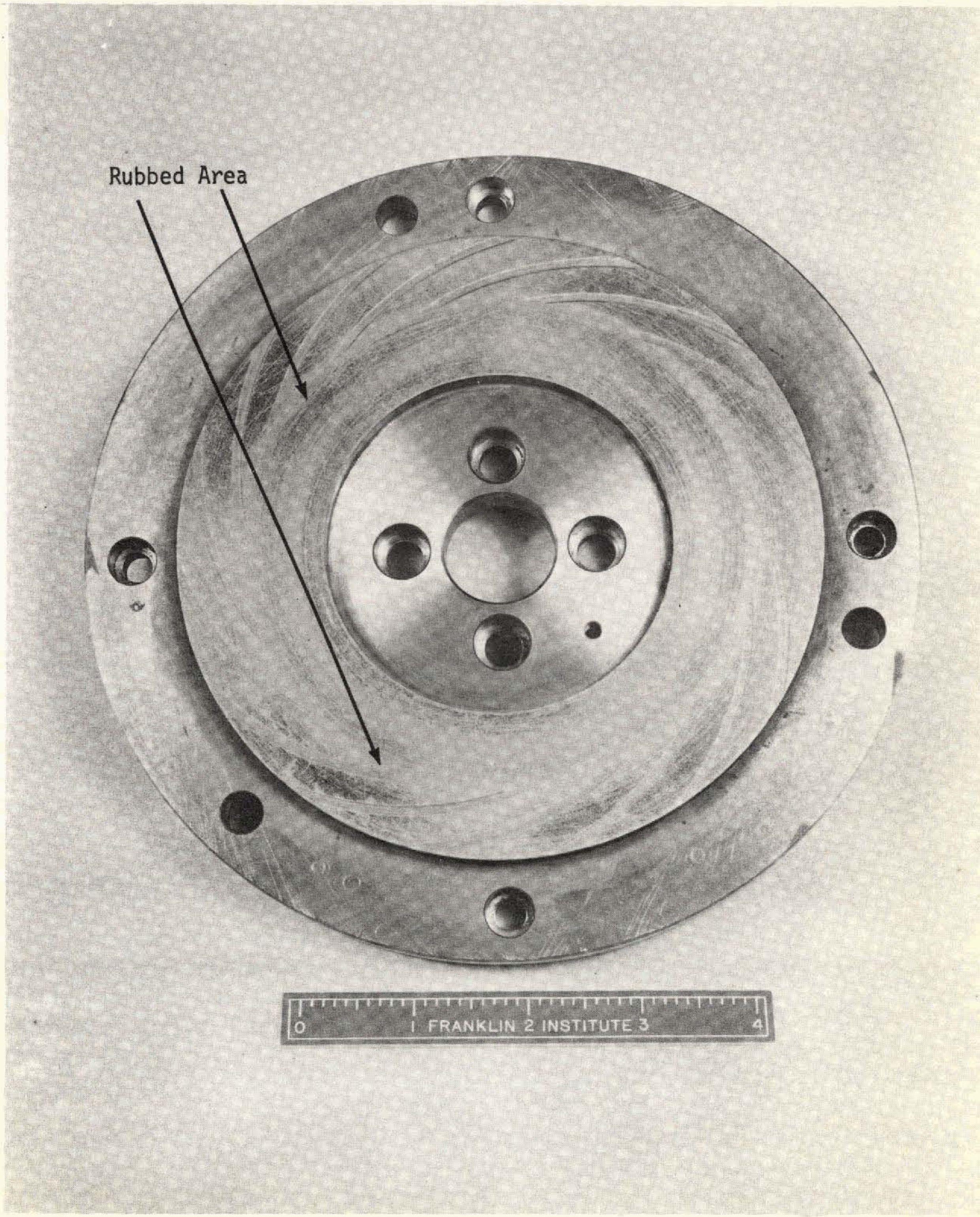

Figure 7-25. Thrust Bearing No. 1, Showing Wear After 15,000 Start-Stop Cycles

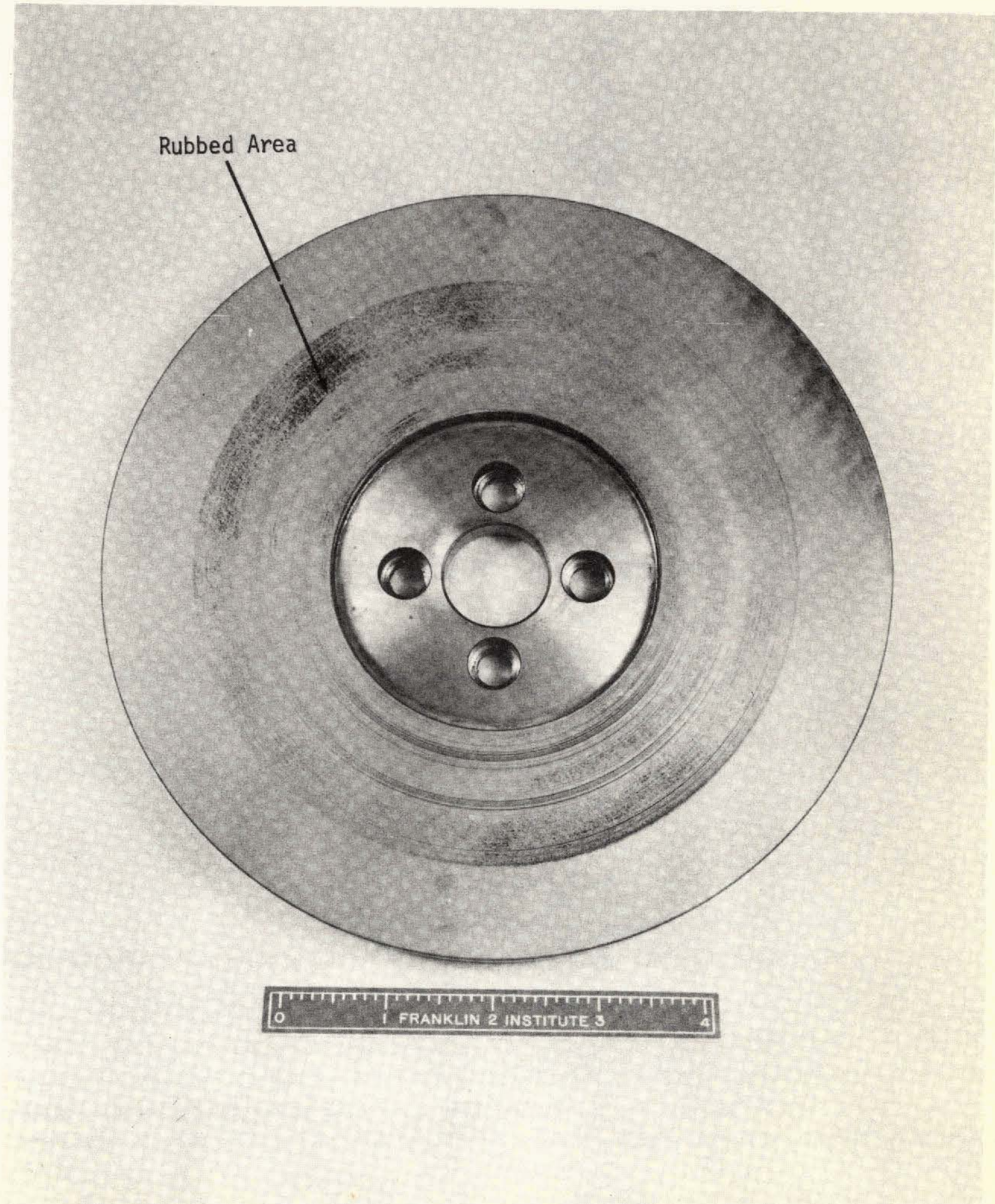

Figure 7-26. Thrust Runner No. 1, Showing Wear After 15,000 Start-Stop Cycles

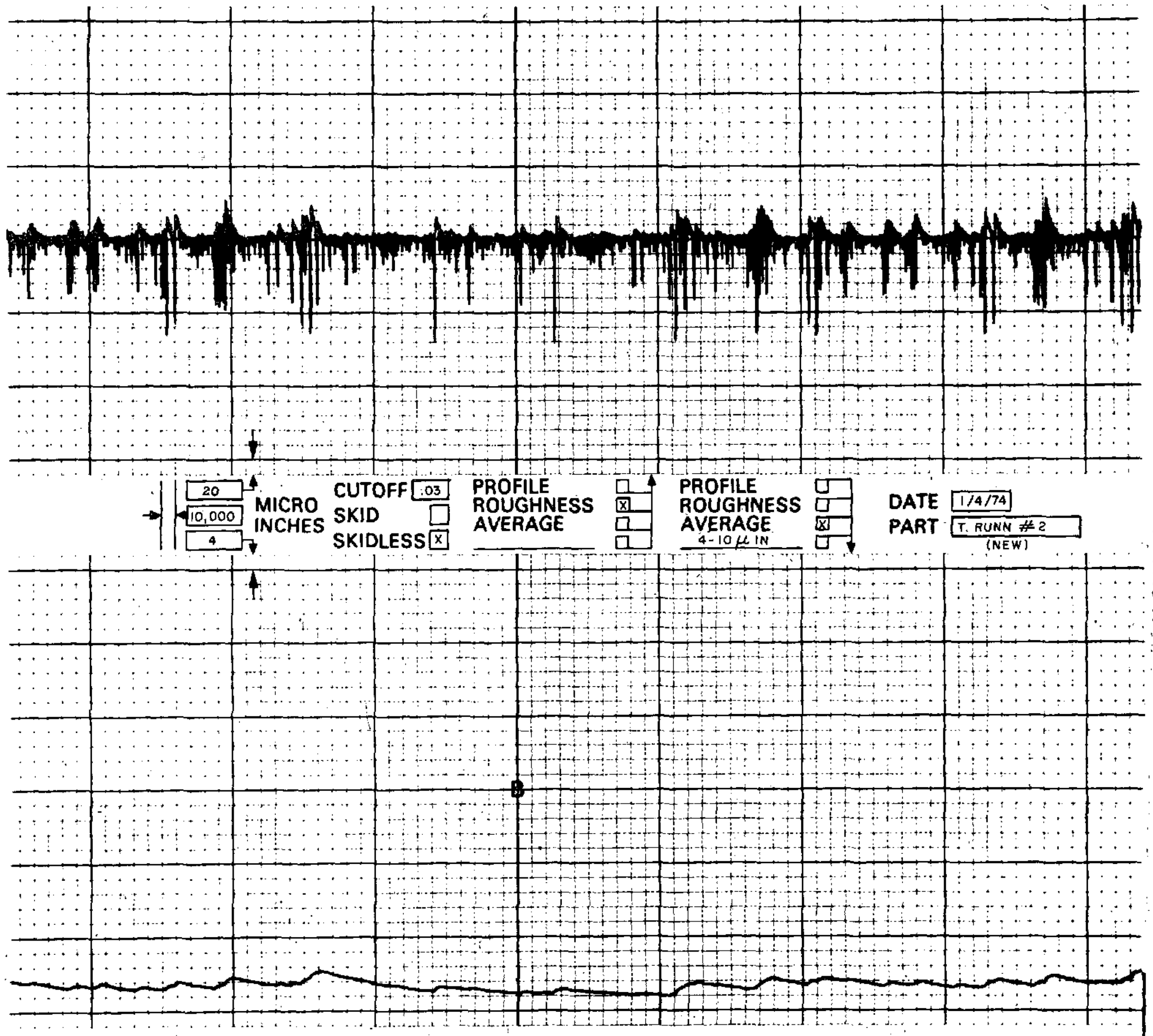

Figure 7-27. Surface Finish, Thrust Runner #2 (New)

F-C3691

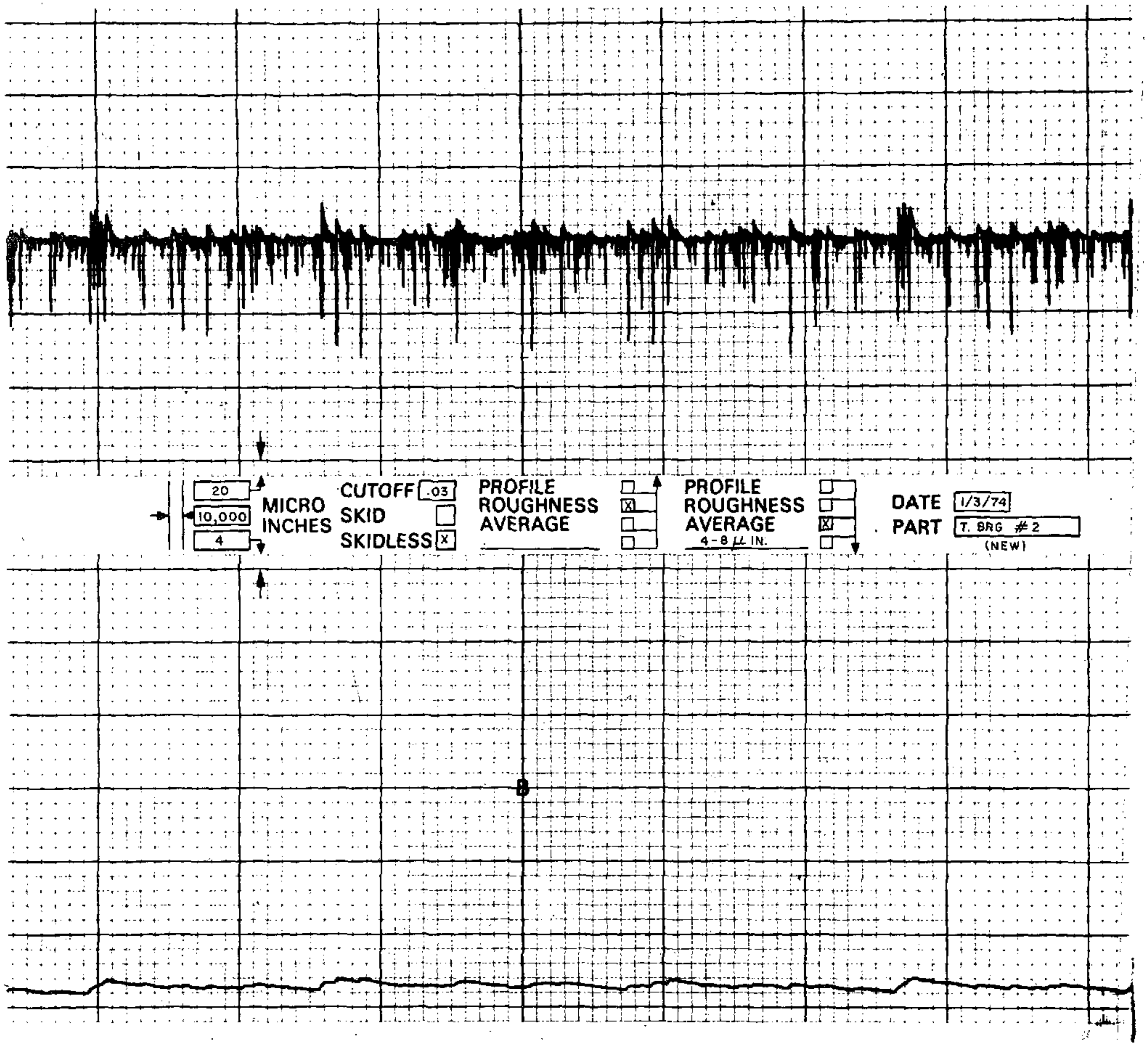

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Figure 7-28. Surface Finish, Thrust Bearing No. 2 (New)

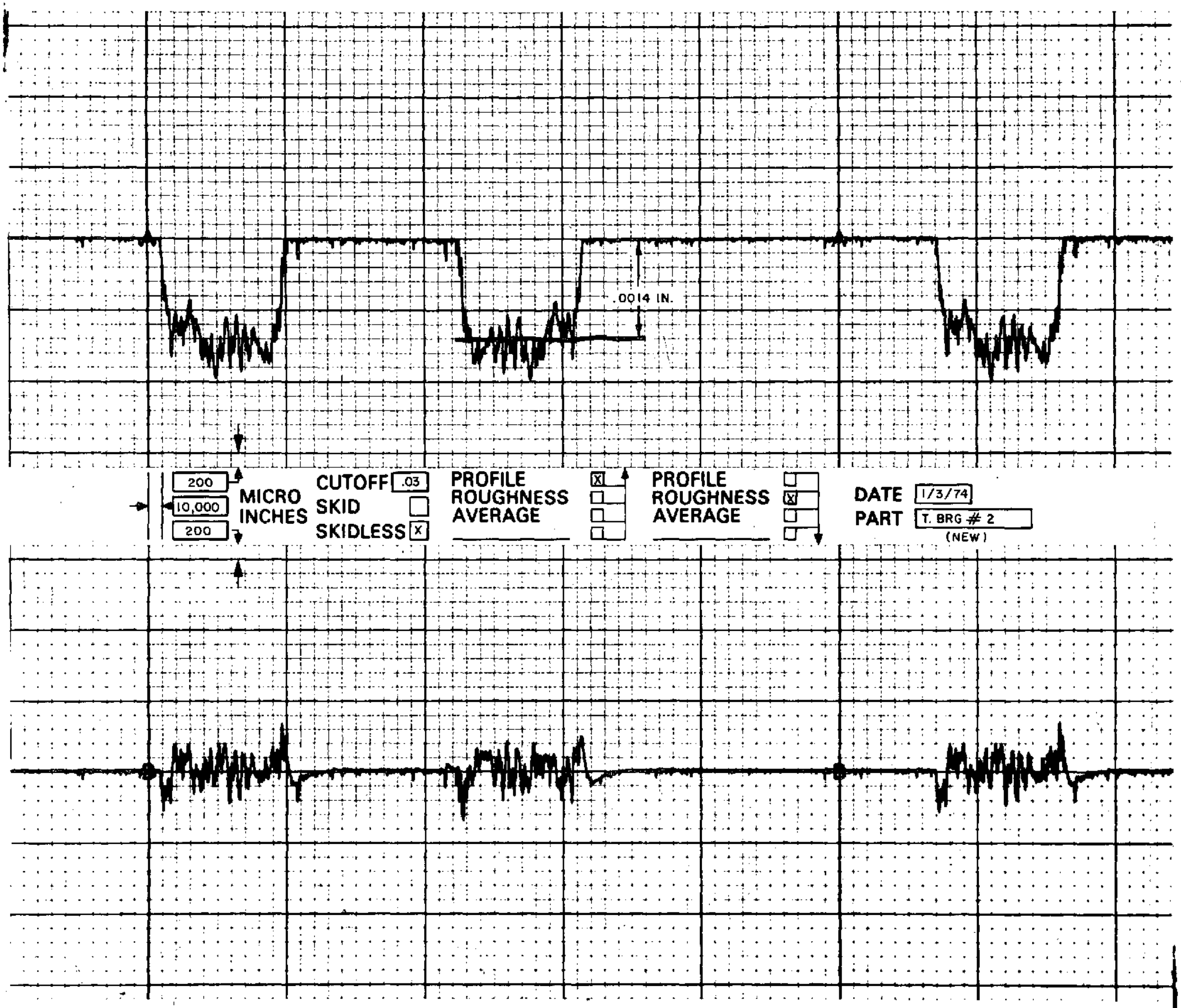

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Figure 7-29. Groove Depth, Thrust Bearing No. 2

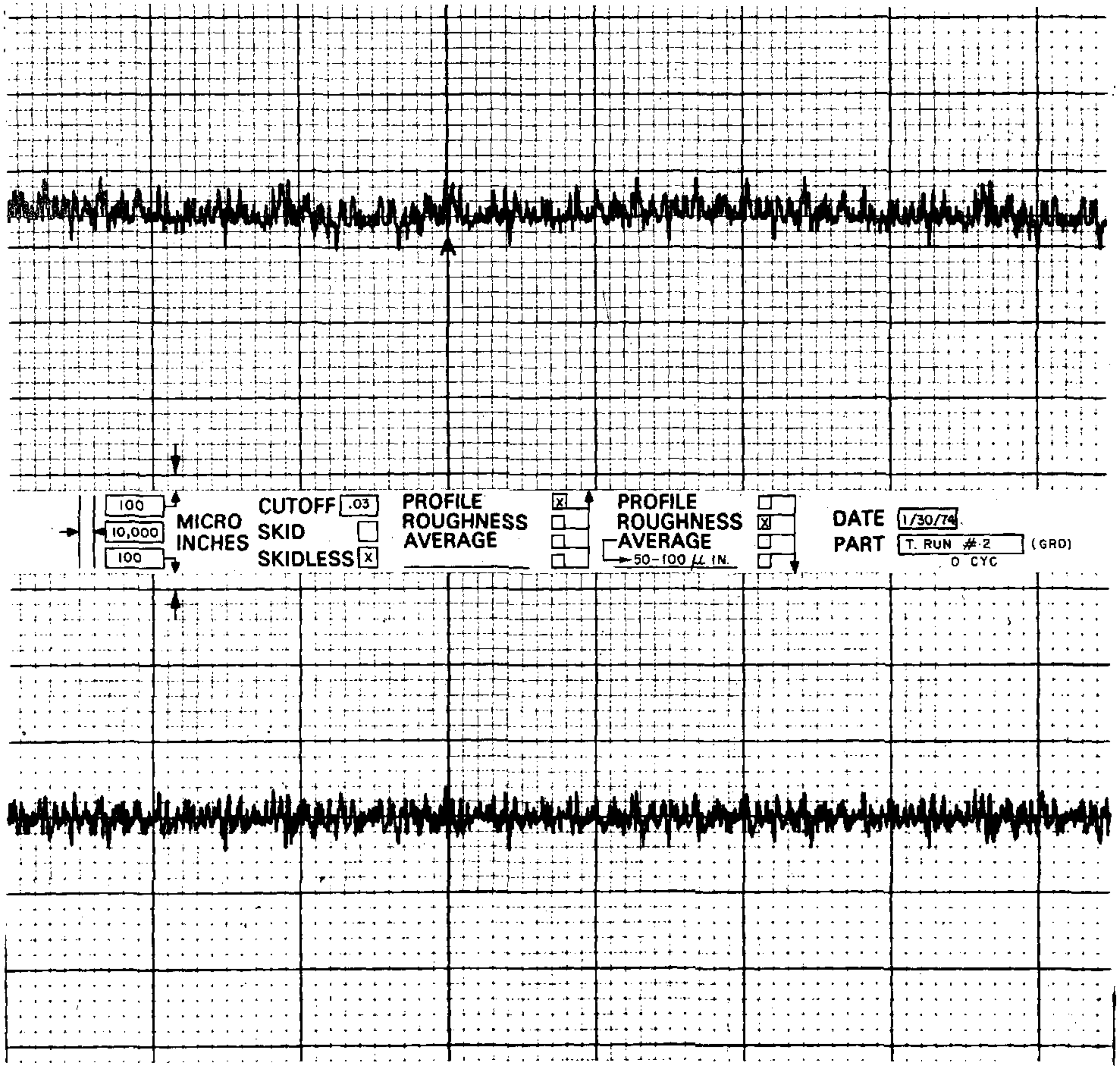

Figure 7-30. Surface Finish, MoS_2 Coating Thrust Runner No. 2, After Grinding to Required Coating Thickness

F-C3691

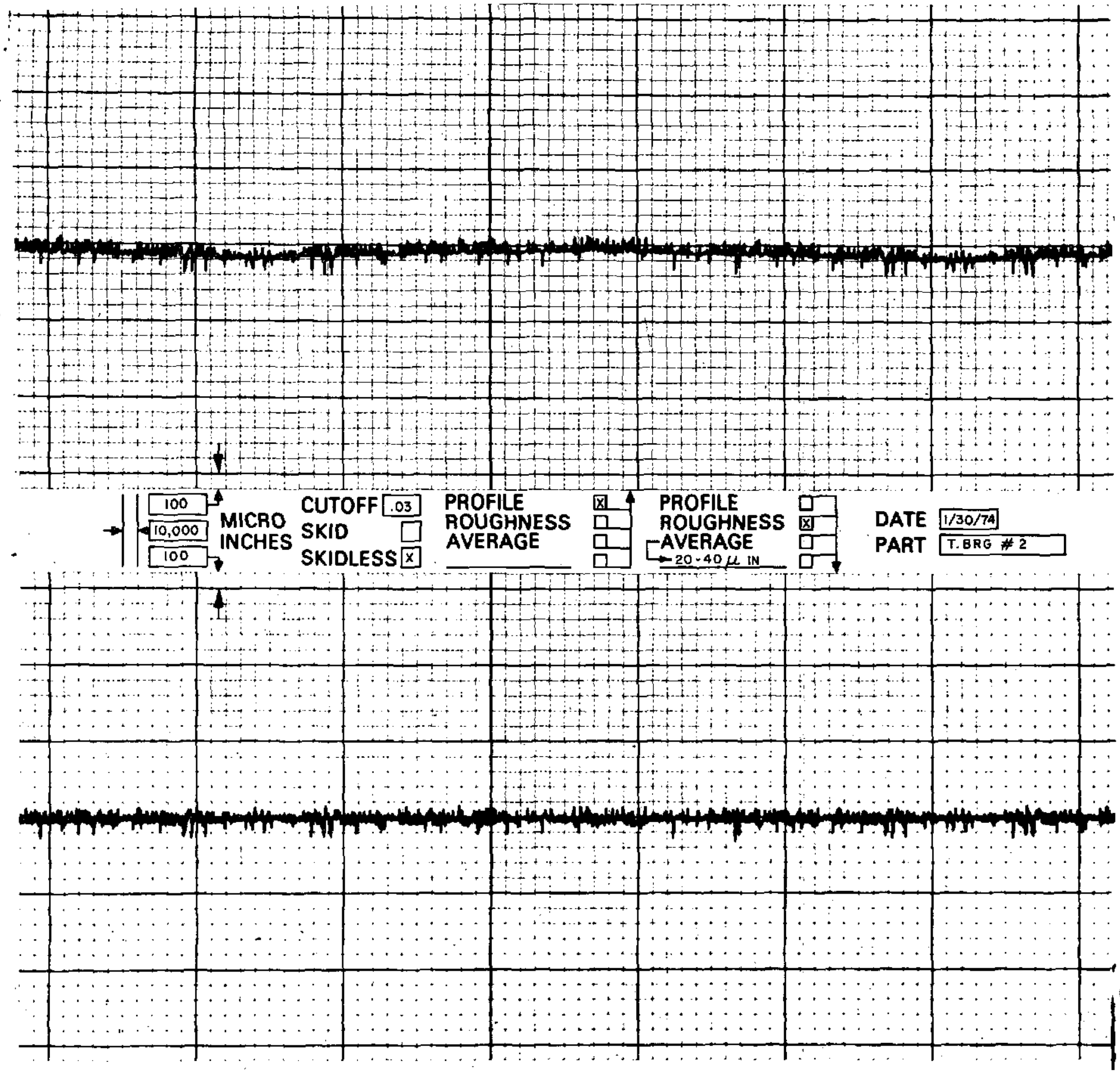

Figure 7-31. Surface Finish, MoS_2 Coating Thrust Bearing No. 2, After Grinding to Required Coating Thickness

F-C3691

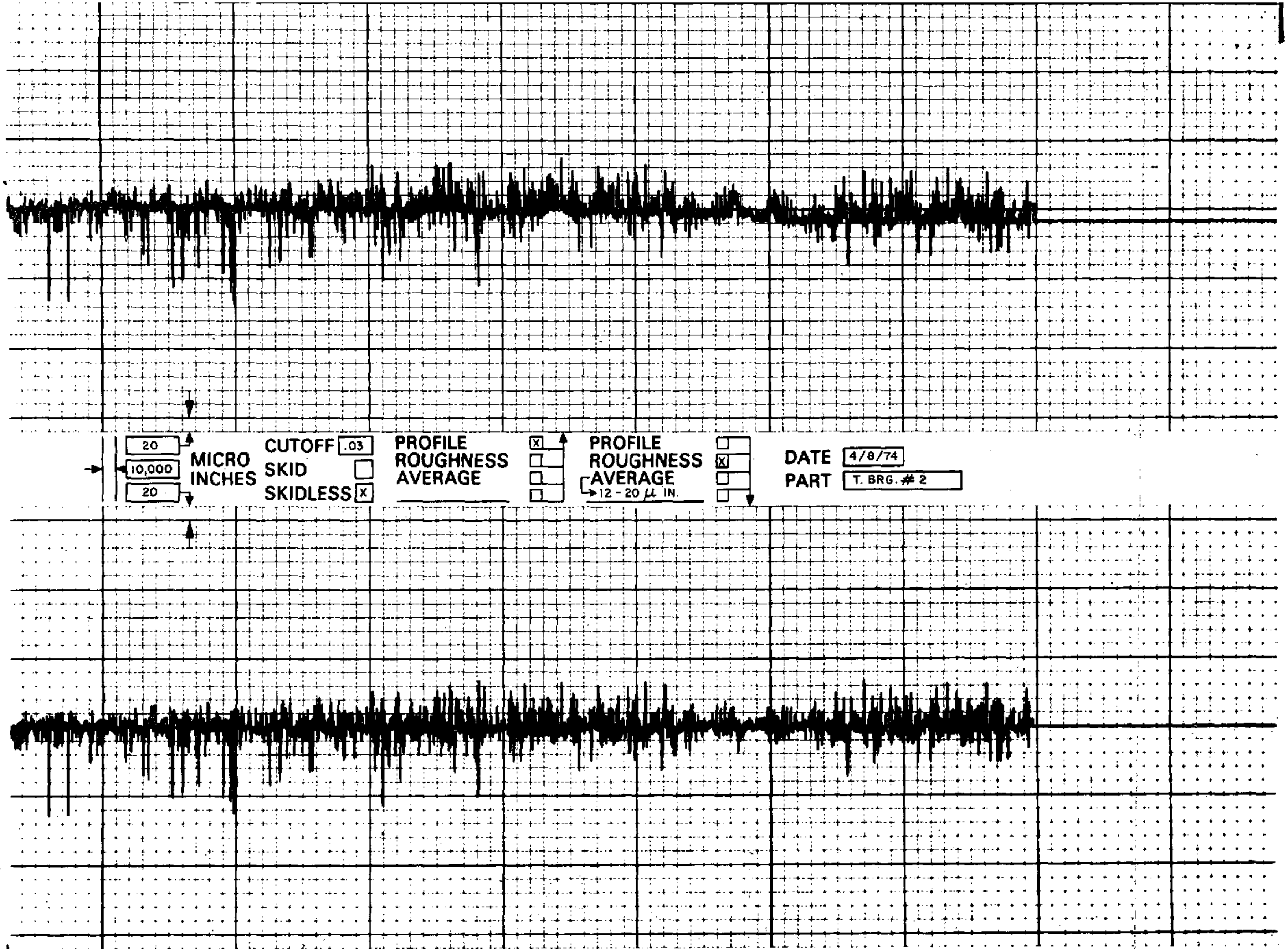

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Figure 7-32. Thrust Bearing No. 2, Surface Contour at Failure, 1 Cycle, 156N (35 lbf) Load

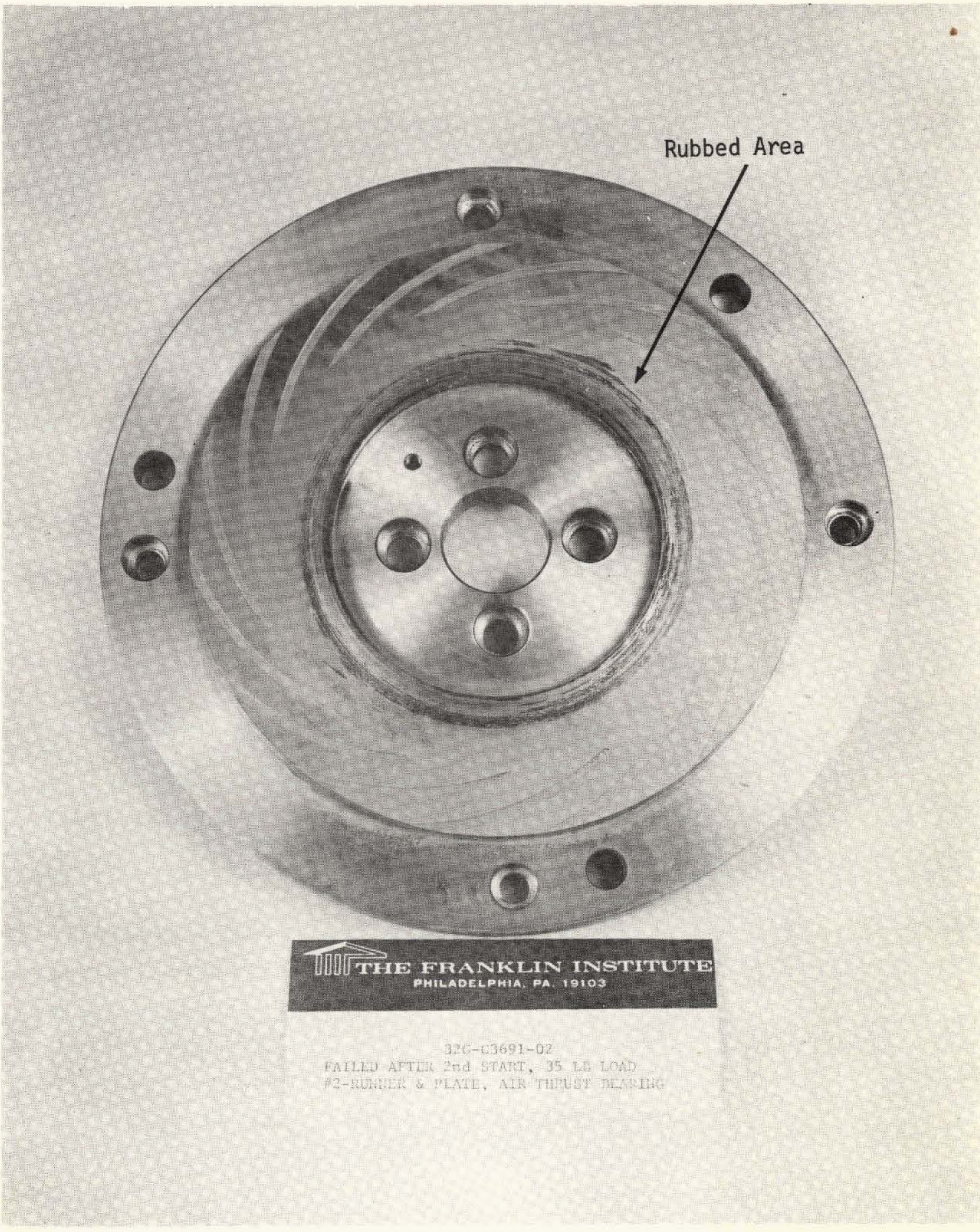

Figure 7-34. Thrust Bearing No. 2, Failure at 1 Cycle, 156N (35 lbf) Load, MoS_2 Coated

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