NASA TECHNICAL NOTE

NASA TN D-7656

NASA TN D-7656

EVALUATION OF CHROMIUM OXIDE AND MOLYBDENUM DISULFIDE COATINGS IN SELF-ACTING STOPS OF AN AIR-LUBRICATED RAYLEIGH STEP THRUST BEARING

by Zolton N. Nemeth

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1974

1. Report No.
NASA TN D-7656

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
EVALUATION OF CHROMIUM OXIDE AND MOLYBDENUM DISULFIDE COATINGS IN SELF-ACTING STOPS OF AN AIR-LUBRICATED RAYLEIGH STEP THRUST BEARING

5. Report Date
MAY 1974

6. Performing Organization Code

7. Author(s)
Zolton N. Nemeth

8. Performing Organization Report No.
E-7777

10. Work Unit No.
501-24

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Note

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
Two coatings for a Rayleigh step thrust bearing were tested when coasting down and stopping under self-acting operation in air. The thrust bearing had an outside diameter of 8.9 cm 3.5 in.), an inside diameter of 5.4 cm (2.1 in.), and nine sectors. The load was 73 N (16.4 lbf). The load pressure was 19.1 kN/m^2 (2.77 $lbf/in.^2$) on the total thrust bearing area. The chromium oxide coating was good to 150 stops without bearing deterioration, and the molybdenum disulfide coating was good for only four stops before bearing deterioration. The molybdenum disulfide coated bearing failed after nine stops.

17. Key Words (Suggested by Author(s))
Bearing
Gas bearing
Rayleigh step thrust bearing
Coating

18. Distribution Statement
Unclassified - unlimited
Category 15

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	25	$3.00

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

EVALUATION OF CHROMIUM OXIDE AND MOLYBDENUM DISULFIDE COATINGS IN SELF-ACTING STOPS OF AN AIR-LUBRICATED RAYLEIGH STEP THRUST BEARING

by Zolton N. Nemeth

Lewis Research Center

SUMMARY

A Rayleigh step thrust bearing was tested when coasting down and stopping with two types of surface coatings. One surface coating was a soft solid lubricant molybdenum disulfide (MoS_2) burnished onto the surface. The second coating was a hard ceramic chromium oxide (Cr_2O_3). The thrust bearing had an outside diameter of 8.9 centimeters (3.5 in.), an inside diameter of 5.4 centimeters (2.1 in.), and nine sectors. The load was 73 newtons (16.4 lbf). The load pressure on the bearing was 19.1 kilonewtons per square meter (2.77 lbf/in.^{2}) on the total area.

The Cr_2O_3 coating was good for 150 stops without deterioration and the MoS_2 surface was good for only four stops without bearing deterioration. The chromium oxide surface was smoother after 150 stops than at the start. The MoS_2 surface was damaged after nine stops to the extent that the surface roughness peaks were greater than the theoretical hydrodynamic film thickness.

INTRODUCTION

The tilting pad gas journal bearings with clamping preload and the thrust gas bearing used to support the rotating assembly in the Brayton rotating unit (BRU) must be started and shut down with external pressurization (ref. 1). External pressurization is maintained to the bearings until design speed is reached after which it is discontinued and the bearings operated hydrodynamically (self-acting). The external pressurization lifts the pads from the shaft and floats the shaft in the bearings. The bearing surfaces are separated and contact does not occur in normal operation, although inadvertent rubbing might occur during momentary bearing instability and shock.

To prevent damage to the contacting bearing surfaces, the bearings were made of

M-50 steel and the shaft was coated with flame plated tungsten carbide. This coating was sufficient to prevent damage in the operation of the BRU machine.

A more efficient coating for both the shaft and bearing surfaces was required for the Brayton (gas) cycle turbomachine (ref. 2) and a plasma sprayed coating of chromium oxide (Cr_2O_3) was developed. The tilting pad bearings in this machine were designed such that external pressurization was not required during the startup and shutdown. This was accomplished by eliminating the clamping load requirement by the use of stiffer flexure mounts and by operating the machine in the vertical position. However, some rubbing occurs between the journal tilting pads and shaft during startup and shutdown when the speed is too low to generate a gas film. A coating was therefore applied to minimize damage from this rubbing.

The thrust bearing still required external pressurization during startup and shutdown even when the shaft was operated in the horizontal position or zero gravitational field. The thrust bearing may be subjected to high aerodynamic axial loads.

The requirement for externally pressurizing the bearings is a large weight and volume penalty to pay in the operation of space power machinery and future contemplated advanced turbojet engines (ref. 3). Sufficiently high pressures may not be available from the space power machinery or turbojet engines to store for use in subsequent starts and stops. This would necessitate a replaceable bottled source of pressurized gas.

Material combinations and coatings have been investigated by many (refs. 3 to 5) in an effort to eliminate the jacking gas requirement by reducing starting friction and wear damage during rubs. From the standpoint of wear resistance, Cr_2O_3 coatings have been the most successful in gas bearing applications for bearings operating below 700 K (800° F). Most work in the study of start-stop unlubricated bearings has been with lightly loaded or unloaded pivoted pad journal bearings.

The object of this investigation was to study the effect of repeated stopping on a full size Rayleigh step thrust bearing under self-acting (hydrodynamic) operation. The air turbine drive in this test apparatus did not have enough capacity to start the rotation of the thrust bearing without external pressurization of the bearing. Start rubbing condition (duration) is dependent on the drive turbine characteristics. Stop rubbing is dependent on the moment of inertia of the rotor. Two coatings were used, a burnished soft solid lubricant molybdenum disulfide (MoS_2) and a plasma sprayed hard Cr_2O_3 coating. The bearing was loaded by the gravity weight of the shaft, 73 newtons (16.4 lbf). The load pressure was 19.1 kilonewtons per square meter (2.77 lbf/in.^{2}) on the total area and 30.9 kilonewtons per square meter (4.48 lbf/in.^{2}) on the ridge area. The shaft was allowed to coast down under self-acting operation to a complete stop. Air was used as the lubricant.

The Rayleigh step thrust bearing size and configuration was similar to the thrust bearing in the Brayton rotating unit. The thrust bearing had an outside diameter of 8.9 centimeters (3.5 in.), an inside diameter of 5.4 centimeters (2.1 in.), and nine sectors.

APPARATUS

Bearing Test Apparatus

The test apparatus was used previously for a journal tilting pad gas bearing investigation (ref. 6). It was modified to accept the new test thrust bearing and to add the capability of measuring the thrust bearing friction torque. The test apparatus before modification is fully described in reference 6. Briefly it consists of a vertically oriented rotor supported by two identical tilting pad journal bearings and an externally pressurized 5.1-centimeter- (2.0-in.-) diameter thrust bearing at the lower end of the rotor. The rotor has an air turbine mounted on the upper end, two journal bearings 28 centimeters (11 in.) apart, and a thrust surface at the lower end. Each journal bearing pad is individually supported on a pivot.

The test apparatus in its present form is shown in figure 1. A closeup of the modification is shown in a photograph and a schematic drawing in figure 2. The externally pressurized support thrust bearing used previously was replaced by the thrust bearing, a self-alining gimbal support, and an externally pressurized gas bearing load support with a bearing friction force transducer. The weight of the shaft, 73 newtons (16.4 lbf), constituted the applied thrust load. The load pressure was 19.1 kilonewtons per square meter (2.77 lbf/in.^{2}) on the total area and 30.9 kilonewtons per square meter (4.48 lbf/in.^{2}) on the bearing ridge area. The calculated polar mass moment of inertia of the shaft and the thrust bearing runner was 5.2×10^{-3} kilogram-meter^2 (0.045 in.-lb sec^2). Thrust bearing friction force was measured by a force transducer (an unbonded resistance strain gage), which was connected to the outer diameter of the floating housing. Thrust bearing friction force and shaft speed were recorded continuously on a two-pen recorder. Since the Rayleigh step thrust bearing and its housing floated freely in the pressurized gas journal and thrust bearing, the test bearing friction force could be measured directly by the force transducer.

Test Thrust Bearing

Design. - The gas thrust bearing is shown in a drawing in figure 3 and in a photograph in figure 4. The thrust bearing assembly consists of a stator (bearing) and a rotor. The stator is mounted on a self-alining gimbal support. The thrust bearing is a fixed geometry Rayleigh step design. It is single acting where the load can be applied in only one direction, toward the face of the stator. The runner is a flat disk which is attached to the bottom of the rotor. The stator or bearing disk has nine sectors. Each sector consists of a step and a ridge. The step is approximately 15 micrometers (0.0006 in.) high and extends over an angular distance of approximately 15.5°. The ridge extends over 24°. A narrow radial lubricant (air) feed groove separates the adjacent sectors. The thrust bearing is hydrodynamic but has hydrostatic capability. There is an air feed orifice in the center of each of the nine ridge areas.

The test bearing configuration was generally the same as the thrust bearing in the BRU machine in order to study a realistic bearing. The outside diameter was 8.9 centimeters (3.5 in.) and the inside diameter was 5.4 centimeters (2.1 in.).

The performance of the thrust bearing configuration was optimized using the analytical method of reference 7 at the BRU rotating speed of 36 000 rpm with air as the lubricant at 297 K (75° F) and 10^5-newton-per-square-meter (14.7-psia) pressure. The effects on performance of the number of sectors and step height and step angular extent were examined. The predicted thrust bearing performance or self-acting load capacity is shown in figure 5 as a function of film thickness. The minimum rotor speed at which some reasonable thrust bearing film thickness might be achieved is also of interest. A satisfactory bearing minimum film thickness under self-acting operation is generally about 7.5 micrometers (0.3 mil). At touchdown where actual rubbing between the rotor and stator begins the film thickness is less than 7.5 micrometers (0.3 mil). The rubbing minimum film thickness depends on several factors such as bearing face flatness and surface roughness and thermal distortion. The predicted film thickness of the thrust bearing is shown in figure 6. Rotor speed varies from 18 000 rpm down to about 2500 rpm and the load is 73 newtons (16.4 lb), the shaft assembly weight. A speed of 12 300 rpm is required to obtain a film thickness of 7.5 micrometers (0.3 mil) for this bearing.

Bearing material and coating. - The thrust bearing material was hardened M-50 steel and the mating runner material was SAE 4340 steel in one test and hardened M-50 steel in another test. The bearing surfaces of the M-50 and 4340 steel bearing combination were burnished with a soft solid lubricant MoS_2 using a smooth hardwood block. The bearing surfaces of the M-50 and M-50 steel bearing combination were plasma sprayed with Cr_2O_3. The Cr_2O_3 coating was approximately 76 micrometers (3 mils) thick. The thrust bearing surfaces were flat to within 2.5 micrometers (0.0001 in.).

Shaft and Journal Bearings

The journal bearings, while not the focus of the test program, might affect the data of the test thrust bearing; therefore, a brief description of the support system is warranted. The support gas tilting pad bearings and the mating shaft materials were hardened M-50 steel and 17-4 PH stainless steel, respectively. The bearing pad and shaft surfaces were reworked before testing of the gas thrust bearing to recondition them from previous testing and to obtain the desired clearance in the journal hearings. The shaft bearing surfaces were chrome plated and ground to size.

Air Supply System

Service air (8.3×10^5-N/m^2 or 120-psi supply) was used for the pressurized operation of the bearings, both the journal and thrust bearing, and the drive turbine. The pressurized air to the bearings and drive was treated to remove moisture, oil vapor, and solid particles. The pressure was individually regulated to each bearing. Ambient air in the room was used for self-acting operation of the thrust bearing. The temperature of the room was kept at a constant 297 K (75° F).

Instrumentation

Capacitance probes were used to measure the displacement and vibration of the thrust bearing and the shaft. The placement of the probes at the journal bearing locations was the same as previously reported in reference 6. Four capacitance probes were used at the thrust bearing, 90° apart at the outer diameter. One of the probes was attached to the thrust bearing stator and the other three were attached to the test rig frame. Two probes (including the one attached to the bearing stator) sensed the rotor motion and film thickness. The other two probes sensed the stator movement.

Thrust bearing friction force was measured by a force transducer (an unbonded wire-wound resistance strain gage) which was connected to the outer diameter of the floating support. The bearing stator floated freely in a pressurized gas journal and thrust bearing enabling the force to be measured directly and accurately over the entire bearing friction force range. The bearing friction varied from the very low value under self-acting operation to a quite high value at bearing contact.

Rotor speed was measured by a magnetic probe and indicated on an electronic counter. Six shallow holes on the upper diameter of the shaft produced a signal in the magnetic probe that gave a direct reading in rpm on the counter and provided for electronic speed control.

The data were recorded on a 14-channel FM tape recorder for readout after the completion of the experiment. Bearing friction force and shaft speed were also recorded on a two-pen strip chart recorder.

PROCEDURE

The thrust bearing was floated by pressurizing and then brought up to a speed of 16 000 rpm. At this speed, external pressurization to the thrust bearing was shut off rapidly, by closing of a solenoid valve, after which the thrust bearing was self-acting. The bearing was operated self-acting for 10 minutes. Then the drive turbine air was shut off causing the bearing to coast down to a stop. This was repeated and each time the bearing was run self-acting for 10 minutes at 16 000 rpm to determine whether it was capable of self-acting operation after the previous stop. This routine, start-stop procedure was carried out 150 times or until the thrust bearing failed. Bearing failure was defined as the inability of the bearing to become self-acting at 16 000 rpm.

The data were continuously recorded on a tape recorder. The thrust bearing speed and friction force were also continuously recorded on a two-pen recorder. The capacitance vibration signals were displayed on oscilloscopes while the test was being run.

Thrust bearing film thickness was monitored during both externally pressurized and self-acting operation. The read-out was direct and was obtained by setting the probe output to zero with the thrust bearing faces in contact at zero speed.

Touchdown speed, the speed of the bearing at which initial contact is made between the bearing surfaces under hydrodynamic coastdown was determined. Bearing film thickness could not be used to determine the touchdown speed because of the very small film thickness and of no abrupt change in the film thickness at touchdown. The touchdown speed was determined from the bearing friction and speed curves. At touchdown the slopes of the curves changed rapidly.

The bearing surfaces were examined at the end of the test with a particular pair of surfaces. No inspection was done until tests were completed except once at the start of testing with MoS_2 coated bearings since to have disassembled the bearing at various steps during the test might have caused an adverse effect by altering the alinement.

RESULTS AND DISCUSSION

The results of the experimental investigation are presented in figures 7 to 17. The resistance to surface damage of two thrust bearing coatings, one a soft lubricant and the other a hard ceramic, to repeated stops under self-acting (rubbing) operation is discussed. The effect of surface damage on the performance of the thrust bearing is presented.

Coatings

Molybdenum disulfide (MoS_2). - The Rayleigh step thrust bearing with burnished MoS_2 surfaces operated for nine coastdowns (stops) under self-acting conditions before failure. Failure was defined as the inability of the thrust bearing to become self-acting at 16 000 rpm. Figure 7 shows that, after the fourth touchdown, the touchdown speed increased with each coastdown. At the ninth coastdown the touchdown speed was 12 000 rpm and approaching the 16 000 rpm arbitrary limit. For up to four coastdowns the touchdown speed was constant at about 4000 rpm.

The theoretical film thickness at the different touchdown speeds is shown in figure 8. The theoretical film thickness was about 2.5 micrometers (0.1 mil) for the first four stops (4000 rpm) and was about 7.5 micrometers (0.3 mil) for the last stop (12 000 rpm). The theoretical film thickness at 16 000 rpm is only about 9.1 micrometers (0.36 mil); because of the bearing surface damage this film thickness is insufficient for self-acting operation.

The film thickness was monitored with capacitance probe instrumentation. However, because of the small film thicknesses involved, accurate data could not be obtained. The film thickness data showed qualitatively that touchdown occurred at increasing film thickness for successive coastdowns with the burnished MoS_2 coating.

The measured film thickness under external pressurization of 5.5×10^5 newtons per square meter (80 psi) is about 34 micrometers (1.35 mil). This large film thickness allows the thrust bearing to separate and operate without touching even with the surface roughness peaks approaching 25 micrometers (1 mil).

The thrust bearing surfaces before burnishing with the MoS_2 solid lubricant are shown in figure 4. The same surfaces after burnishing and after two stops under self-acting operation are shown in figure 9. Evidence of rubbing can be seen on both the thrust bearing stator and the mating runner. The rubbing is very light and is at the outer diameter of the stepped sector bearing. The inner dark ring on the runner coincides with the orifice location in the stator and is probably due to the action of the high velocity air flow through the orifices.

The MoS_2 burnished thrust bearing surfaces after nine coastdowns are shown in figure 10. The surface damage is extensive and occurred in the outer half of the bearing area.

Surface radial profile traces of the unworn and worn areas of the thrust bearing stator and mating runner are shown in figure 11. Both thrust bearing stator and mating runner were smooth and flat ($<0.4\ \mu m$ (16 μin.) peak-to-peak roughness) as can be seen in the trace in the noncontacting (unworn) area. Roughness in the worn area of the stator is approximately 6 micrometers (240 μin.) high and in the mating runner 4 micrometers (160 μin.) above and 4 micrometers (160 μin.) below the unworn surface. The profile trace was taken from the inside diameter toward the outside diameter of the disk and recorded from left to right on the trace. The sum of the surface roughness peaks of the bearing runner and stator could easily be greater than the predicted self-acting film thickness at 16 000 rpm for smooth surfaces.

The thrust bearing friction force and rotor speed for coastdowns 1, 5, and 9 are shown in figure 12 for the MoS_2 burnished surfaces. Coastdown 1 is shown in figure 12(a). Friction force about doubles when the thrust bearing becomes self-acting from pressurized operation. The increase in friction force is gradual and smooth. In this transition, the film thickness has decreased from 34 micrometers (1.35 mil) to about 9.1 micrometers (0.36 mil). After 10 minutes of self-acting operation, the drive turbine was shut off and the thrust bearing coasted down while still under self-acting operation. Speed and bearing friction drop off gradually, until about 4000 rpm. At about 4000 rpm bearing friction increases slowly initially as the thrust bearing surfaces come into contact then more rapidly until it jumps to about 7.8 newtons (0.8 kgf), and the bearing friction drops sharply to zero. During the increase of bearing friction, the shaft speed drops rapidly.

This action repeats itself for four coastdowns. At the fourth coastdown some slight damage to the MoS_2 surfaces must have occurred as becomes evident in the following (fifth) coastdown sequence as shown in figure 12(b). There is sharp momentary increase in the bearing friction force as the bearing goes from pressurized operation to self-acting operation. The bearing operates self-acting without any disturbance in friction force for the next 10 minutes until coastdown is initiated. Coastdown 5 is shorter in length of time than coastdown 1 and terminates at a higher speed. Bearing friction force at touchdown is more erratic and jumps to a higher value of about 14 newtons (1.44 kgf).

The damage to the thrust bearing surfaces becomes more severe for each additional coastdown. At the ninth coastdown sequence shown in figure 12(c) surface damage has progressed to the point where it is difficult to achieve self-acting operation at 16 000 rpm (from pressurized operation). The damaged surfaces contact in going self-acting. The friction force reaches about 4.9 newtons (0.5 kgf). Finally self-acting operation is obtained after the high points of the damaged surface are worn away. At the ninth coastdown the touchdown speed is 12 000 rpm. The friction force reached was about 1.1 kilograms. Testing was terminated because of extensive surface damage.

Plasma sprayed chromium oxide (Cr_2O_3). - The Rayleigh step thrust bearing with the plasma sprayed Cr_2O_3 surfaces was run for 150 coastdowns (stops) under self-acting operation. Testing was terminated after 150 coastdowns without experiencing bearing failure. Bearing operation, based on touchdown speed, seemed to improve with the accumulation of coastdowns (fig. 13). Touchdown speed was high initially (7800 to 8600 rpm) but it dropped slowly over the next 90 coastdowns to about 3700 rpm. The touchdown speed remained approximately at a constant 3700 rpm for the next 60 coastdowns. A wear-in process of the Cr_2O_3 surfaces was taking place at touchdown unlike that of the MoS_2 coated surfaces.

The Cr_2O_3 coated thrust bearing surfaces before testing are shown in figure 14. After 150 stops under self-acting operation the same surfaces are shown in figure 15. Rubbing on the surfaces can be seen on both the thrust bearing stator and the mating runner. The rubbing occurred in the outer half of the Rayleigh step bearing. This is the same as for the MoS_2 burnished bearing. The rubbing of the plasma sprayed Cr_2O_3 surfaces did not damage the surfaces but instead produced a polished surface.

The debris from the polishing action was thrown out radially from the bearing and collected on the bearing stator and mating runner surfaces. In the photograph the debris is more evident on the runner surface as a contrasting gray ring against the dark background of the Cr_2O_3 coating. Some debris also collected on the stator step transition to the ridge. The actual color of the debris was a light yellow green suggesting that it might be a mixture "chrome yellow" ($PbCrO_4$) and Cr_2O_3, which is dark green and opaque.

The surface profile traces of the unworn and the worn rubbed areas of the plasma sprayed Cr_2O_3 coated thrust bearing are shown in figure 16. The worn rubbed area of the bearing runner was almost as smooth as the unworn area the noncontacting area. The peak-to-peak surface reading of the unworn area was generally about 0.4 micrometers (16 μin.) but with many pockets. The maximum pocket depth that was recorded was about 6 micrometers (240 μin.). The pockets are present because the plasma sprayed Cr_2O_3 coating is porous. The worn area of the stator had a peak-to-peak height of about 0.4 micrometer (160 μin.). The thrust bearing stator unworn area was smoother than the surface of the mating runner and had fewer pockets. Although the stator rubbed area shows some signs of wear in the outer regions, it is not nearly as extensive as that for the burnished MoS_2 surface.

The thrust bearing friction force and rotor speed for the first (number 1) and the last (number 150) coastdowns are shown in figure 17 for the Cr_2O_3 coated bearing. Two things are apparent from the figure. First, there was no friction spike increase when the thrust bearing was changed over to self-acting operation (for the entire 150 coastdowns), and second the touchdown speed was higher for the first coastdown approximately 7800 to 8600 rpm than for the last (150th) coastdown, 3800 rpm. Peak bearing friction at touchdown was approximately the same at the start and the end of the testing (coastdown 1 and 150). At both times the maximum friction force was about 17.6 newtons (1.8 kgf).

The Cr_2O_3 coated bearing was probably subjected to more severe individual tests initially then the MoS_2 coated surface because of the higher touchdown speeds at the start of the tests. The rotational energy of the rotor is higher the greater the rotor speed. This rotational energy is absorbed by the bearing coating at touchdown in the process of stopping the shaft rotation. In spite of the greater severity of the tests the Cr_2O_3 coating improved with the number of stops.

Dynamic Motion of Thrust Bearing

While not the object of this investigation, the dynamic motion of the thrust bearing was observed during the experiment. The runner was individually balanced to approximately the same very low value in a commercial balancing machine at a low speed (about 1800 rpm) each time before installation into the test rig. The center of gravity eccentricity was approximately 2.5 micrometers (0.1 mil). The thrust bearing developed an instability with large amplitudes of motion if operated beyond 17 000 rpm. No attempt was made to overcome this instability as testing to 16 000 rpm was sufficient for this stop type of testing. Motions of the thrust bearing for speeds up to 16 000 rpm were small and controlled including motions during thrust bearing resonances.

Effect of Thrust Bearing Stops on Journal Bearings

For the 159 stops plus some uncounted preliminary experimental work with the step bearings, no visible damage was sustained by the two journal bearings. This conclusion is based primarily on the absence of any surface rubbing damage on the journals and the unchanged running characteristics as observed by the electronic vibration and distance instrumentation. The tilting pad journal bearings were operated at all times with 550-kilonewton-per-square-meter (80-psig) external pressurization and thus had sufficient load capacity even at low and zero shaft speed. The motion of the journal and tilting pad bearing system during the thrust bearing rubbing stops was erratic and could have shock loaded the gas journal bearings and caused surface damage, but this was not the case in these tests.

SUMMARY OF RESULTS

Two coatings, a soft solid lubricant burnished molybdenum disulfide (MoS_2) and a hard ceramic chromium oxide (Cr_2O_3) were endurance stop tested on Rayleigh step thrust bearings in air. The Rayleigh step bearing had an outside diameter of 8.9 centimeters (3.5 in.) and an inside diameter of 5.4 centimeters (2.1 in.). The bearing had nine sectors. Each sector consisted of a feed groove, a step region, and a ridge region. The step region extended over 15.5° and was approximately 15 micrometers (0.0006 in.) deep. The ridge region extended over 24° and contained an orifice to provide for pressurized operation of the thrust bearing at start. The thrust load on the test bearing was the shaft assembly weight 73 newtons (16.4 lbf). The load pressure was 19.1 kilonewtons per square meter (2.77 lbf/in.^{2}) on the total thrust bearing area and 30.9 kilonewtons per square meter (4.48 lbf/in.^{2}) on the ridge area. The following results were obtained:

1. The Cr_2O_3 coating experienced 150 stops without bearing deterioration.
2. The MoS_2 coating experienced only four stops without bearing deterioration. The bearing failed after nine stops.
3. The profile traces of the two coatings indicated that (a) the Cr_2O_3 surface was smoother after 150 stops than it was at the beginning of the tests, and (b) the MoS_2 sur-

face was damaged after nine stops to the extent that the surface roughness peaks in the damaged area were greater than the predicted self-acting film thickness.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 10, 1974
501-24.

REFERENCES

1. Anon.: Design and Fabrication of the Brayton Rotating Unit (BRU). Rep. APS-5334-R, AiResearch Mfg. Co., March 15, 1971.
2. Frost, A.; Lund, J. W.; and Curwen, P. W.: High-Performance Turboalternator and Associated Hardware. II - Design of Gas Bearings. NASA CR-1291, 1969.
3. Waldron, Warren D.; and Young, William E.: High Performance Bearing Study. MTI-72TR26, Mechanical Technology, Inc. (AFAPL-TR-72-63; AD-757869), July 15, 1972.
4. Grassam, N. S.; and Powell, J. W.: Gas Lubricated Bearings, Butterworth & Co. (London), 1964.
5. Conte, A. A., Jr.: Coatings to Improve Wear Resistance. Mech. Eng., vol. 95, no. 1, Jan. 1973, pp. 18-24.
6. Nemeth, Zolton N.: Dynamic Behavior of Air Lubricated Pivoted-Pad Journal-Bearing - Rotor System. II - Pivot Consideration and Pad Mass. NASA TN D-6606, Feb. 1972.
7. Hamrock, Bernard J.: Optimization of Self-Acting Step Thrust Bearings for Load Capacity and Stiffness. ASLE Trans., vol. 15, no. 3, July 1972, pp. 159-168.

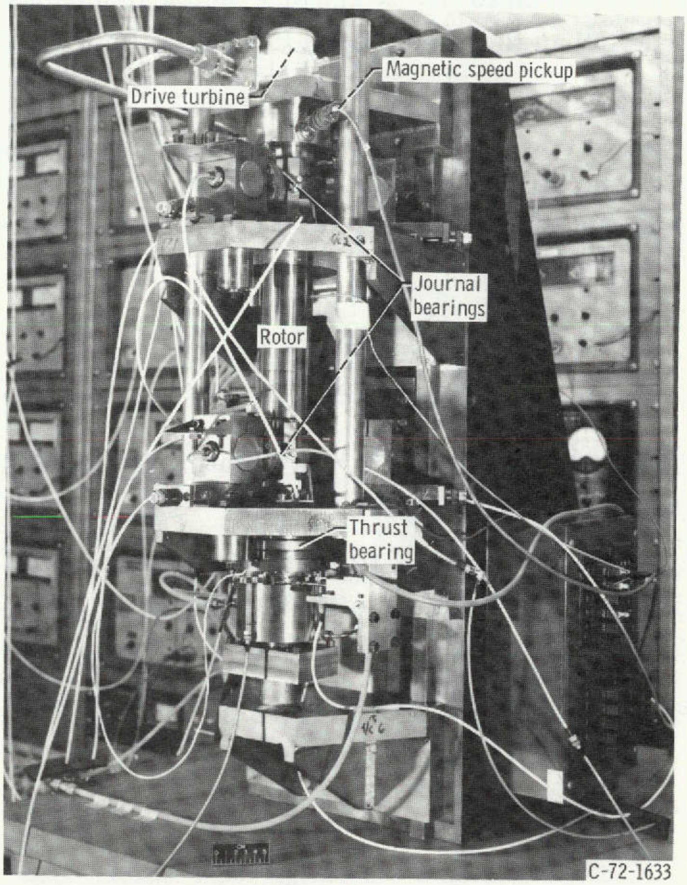


Figure 1. - Thrust bearing test apparatus.

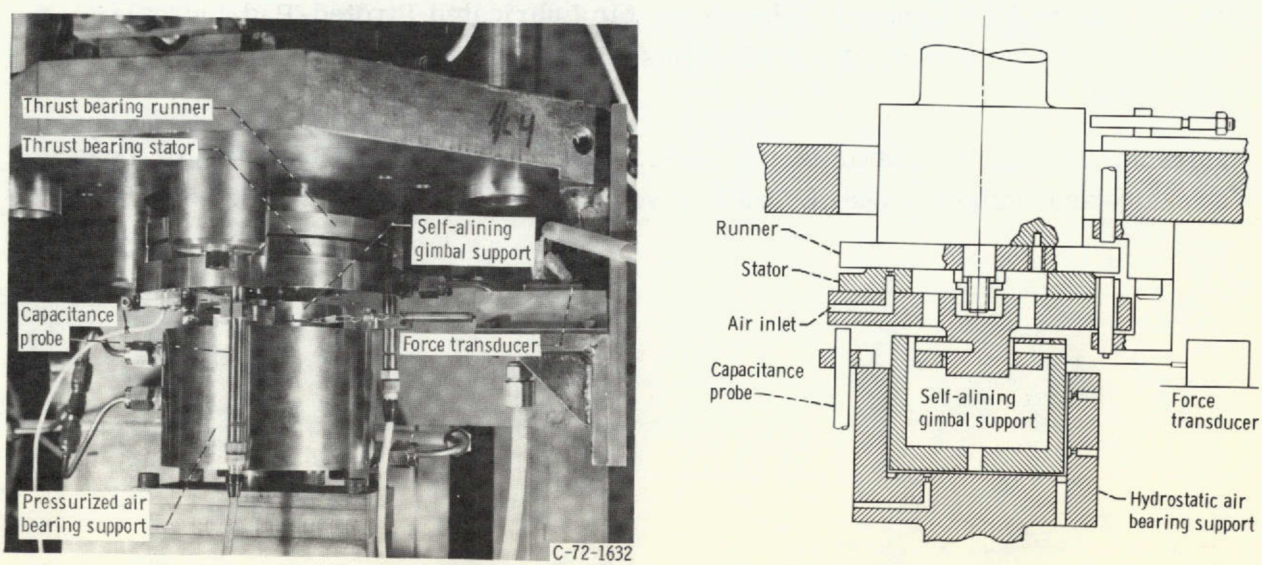


Figure 2. - Thrust bearing and support arrangement.

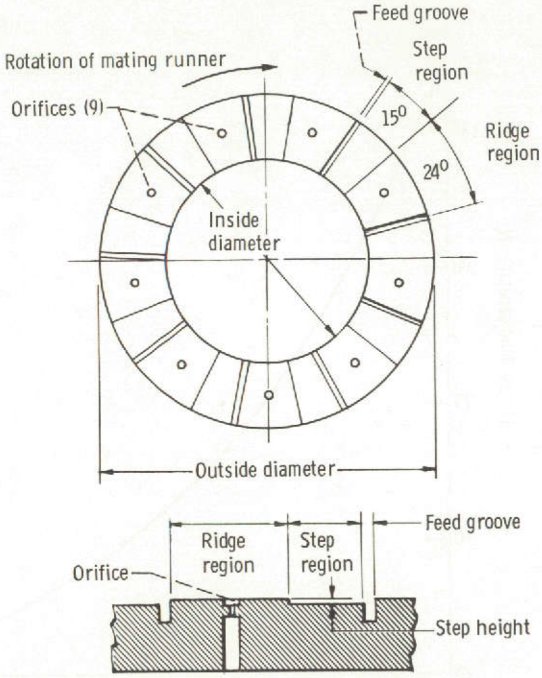


Figure 3. - Rayleigh step thrust bearing.

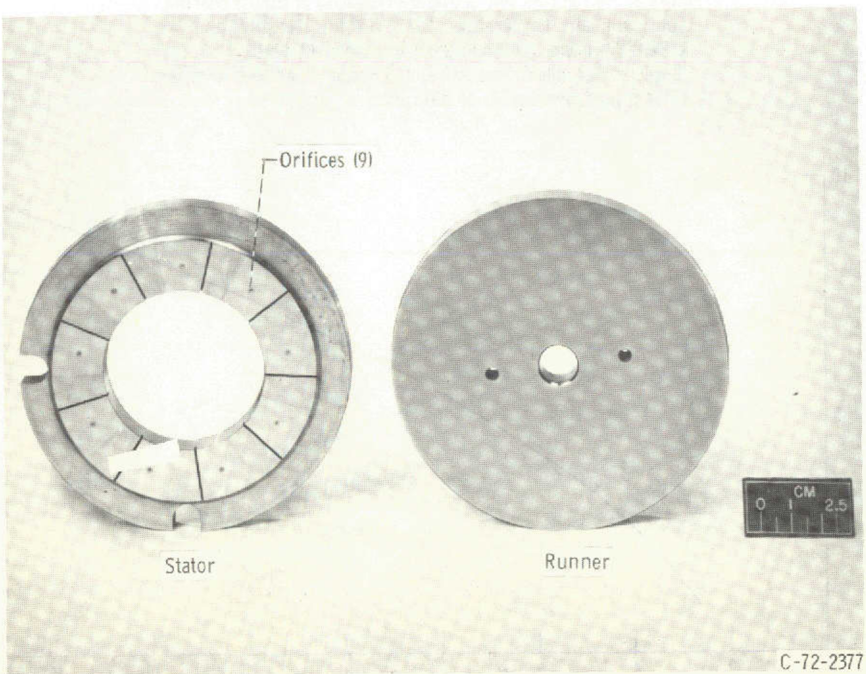


Figure 4. - Rayleigh step thrust bearing stator and mating runner.

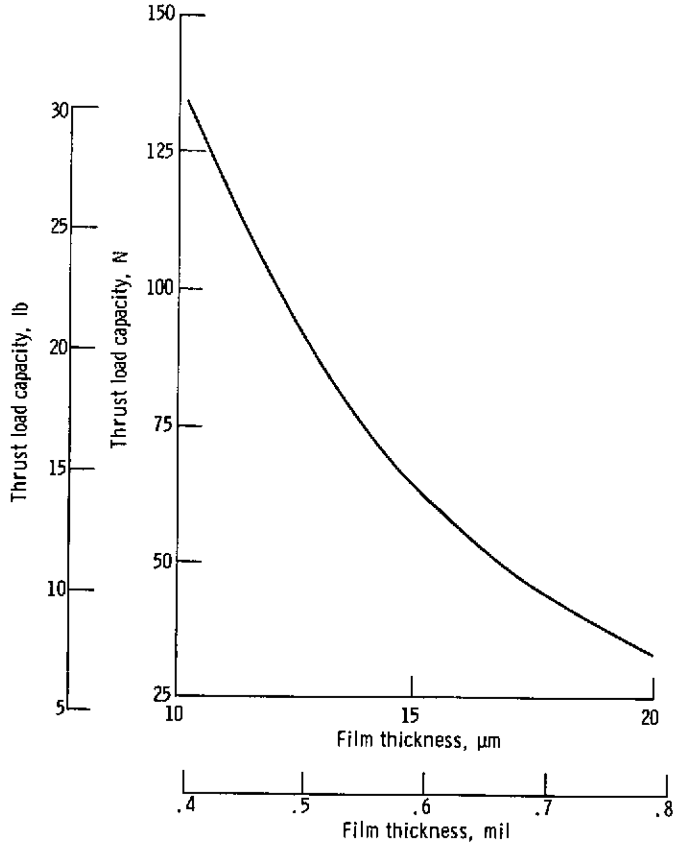


Figure 5. - Predicted self-acting load capacity of thrust bearing. Lubricant, air; temperature, 297 K (75° F); viscosity, µ, 1.8×10^{-5} newton-second per square meter (2.62×10^{-9} lb-sec/in.^{2}); ambient pressure, 10^5 newtons per square meter (14.7 psia); rotor speed, 36 000 rpm.

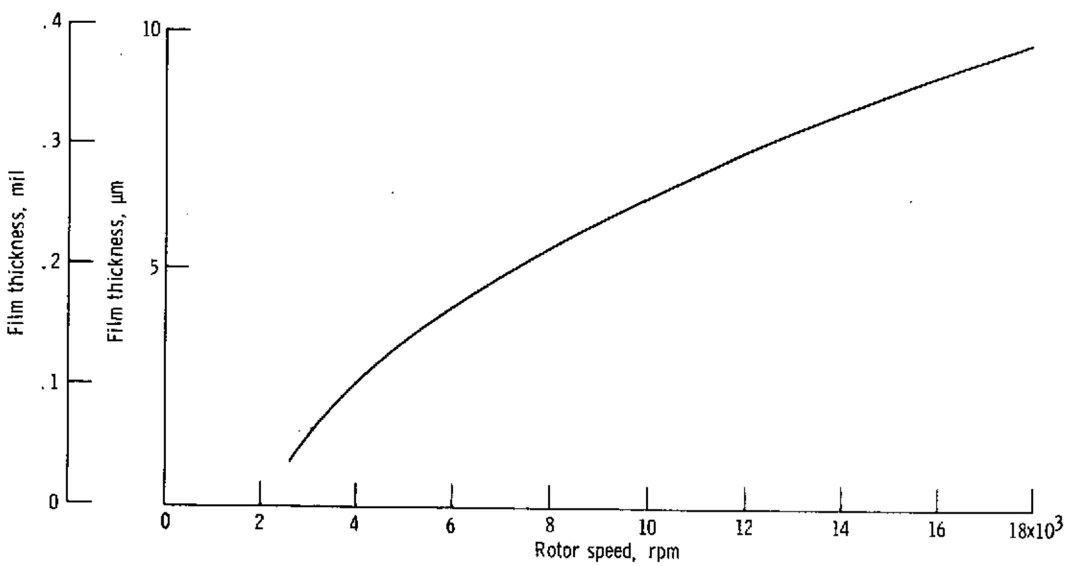


Figure 6. - Predicted self-acting film thickness of thrust bearing plotted against speed with thrust load of 73 newtons (16.4 lb). Lubricant, air; temperature, 297 K (75° F); viscosity, µ, 1.8×10^{-5} newton-second per square meter (2.62×10^{-9} lb-sec/in.^{2}); ambient pressure, 10^5 newtons per square meter (14.7 psia).

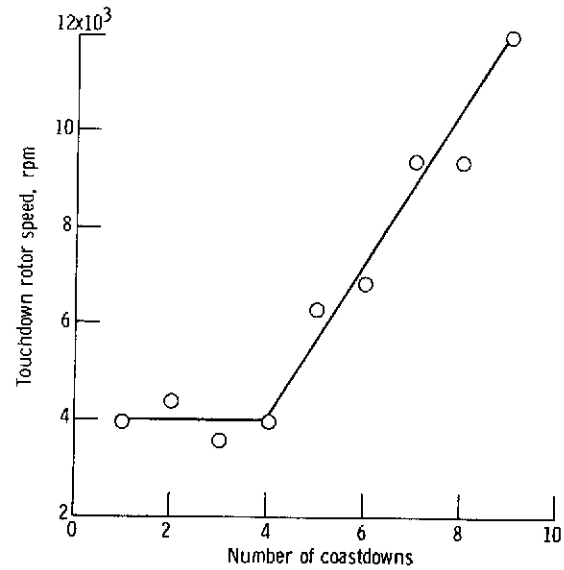


Figure 7. - Touchdown rotor speed plotted against number of coastdowns for stepped-sector air thrust bearing. Bearing surfaces burnished with MoS_2 solid lubricant.

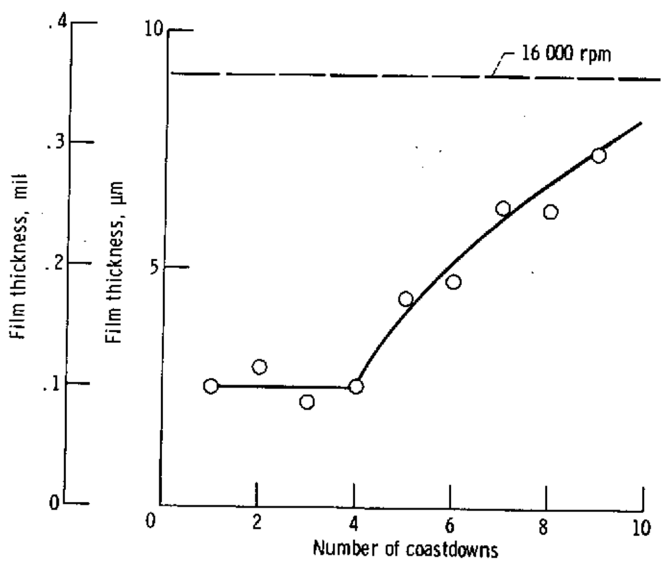
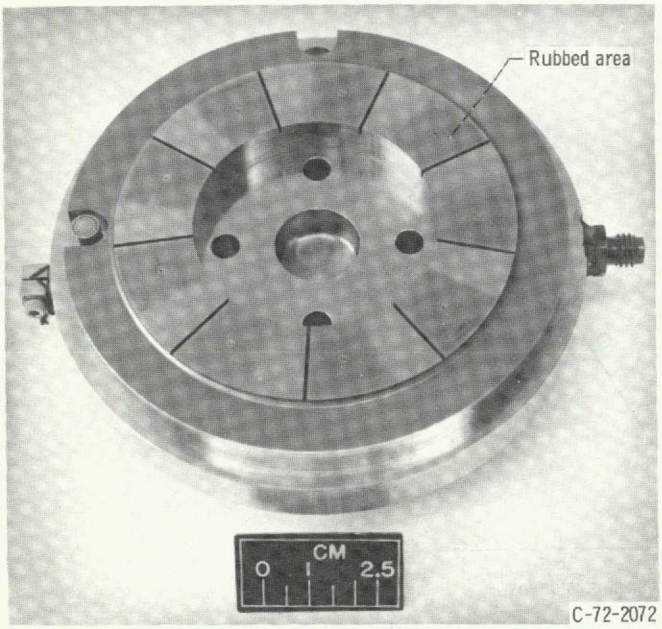
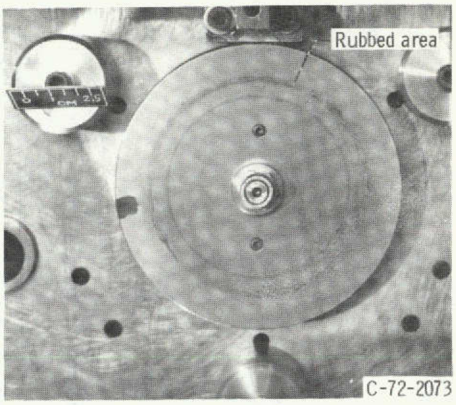


Figure 8. - Theoretical film thickness at touchdown rotor speed plotted against number of coastdowns for stepped-sector air thrust bearing. Bearing surfaces burnished with MoS_2 solid lubricant.



Stator



Runner

Figure 9. - MoS_2 burnished Rayleigh step thrust bearing stator and mating runner after two coastdowns.

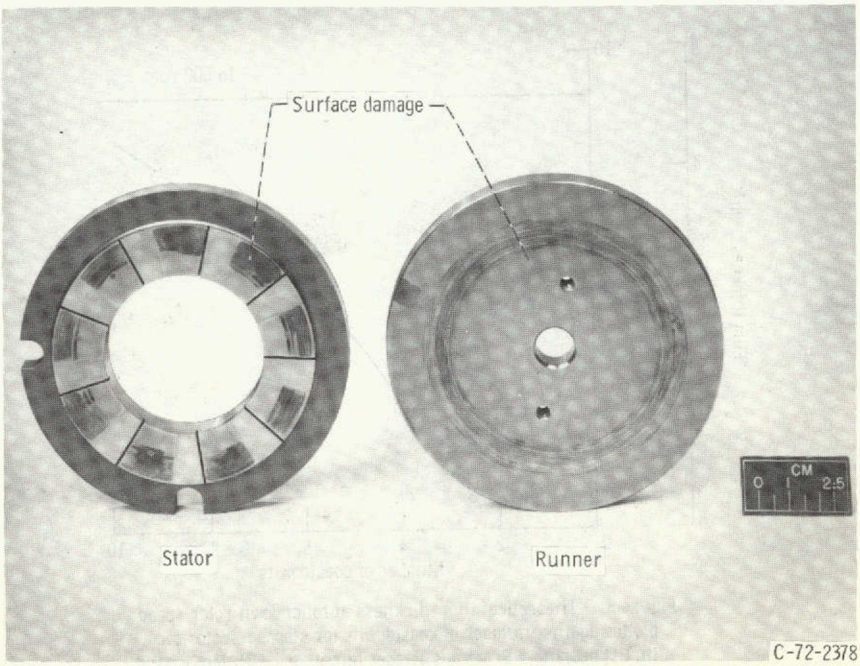
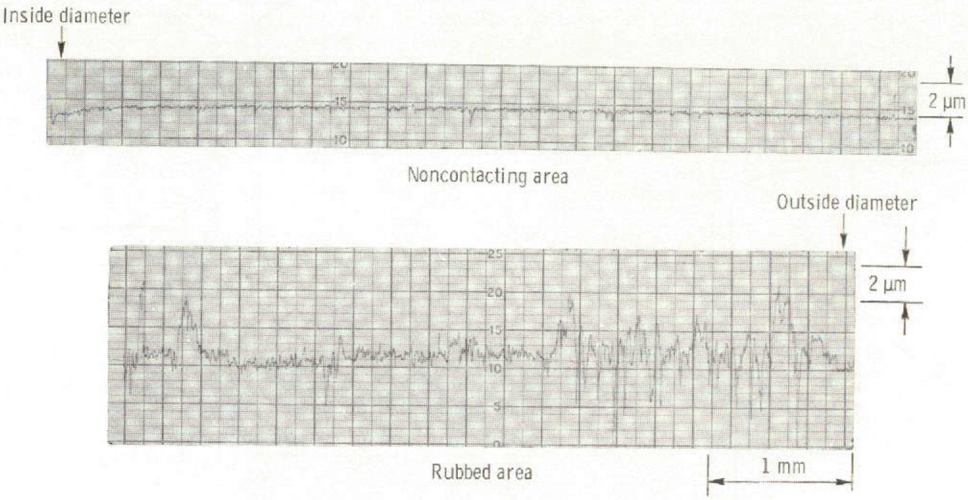
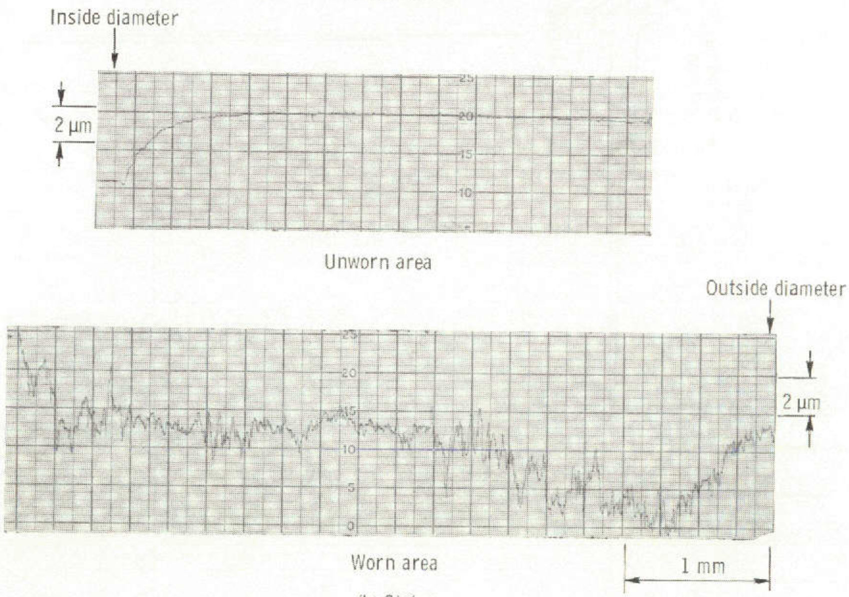


Figure 10. - MoS_2 burnished Rayleigh step thrust bearing stator and mating runner after nine coastdowns.



(a) Runner.



(b) Stator.

Figure 11. - Radial profile trace of MoS_2 burnished thrust bearing stator and runner.

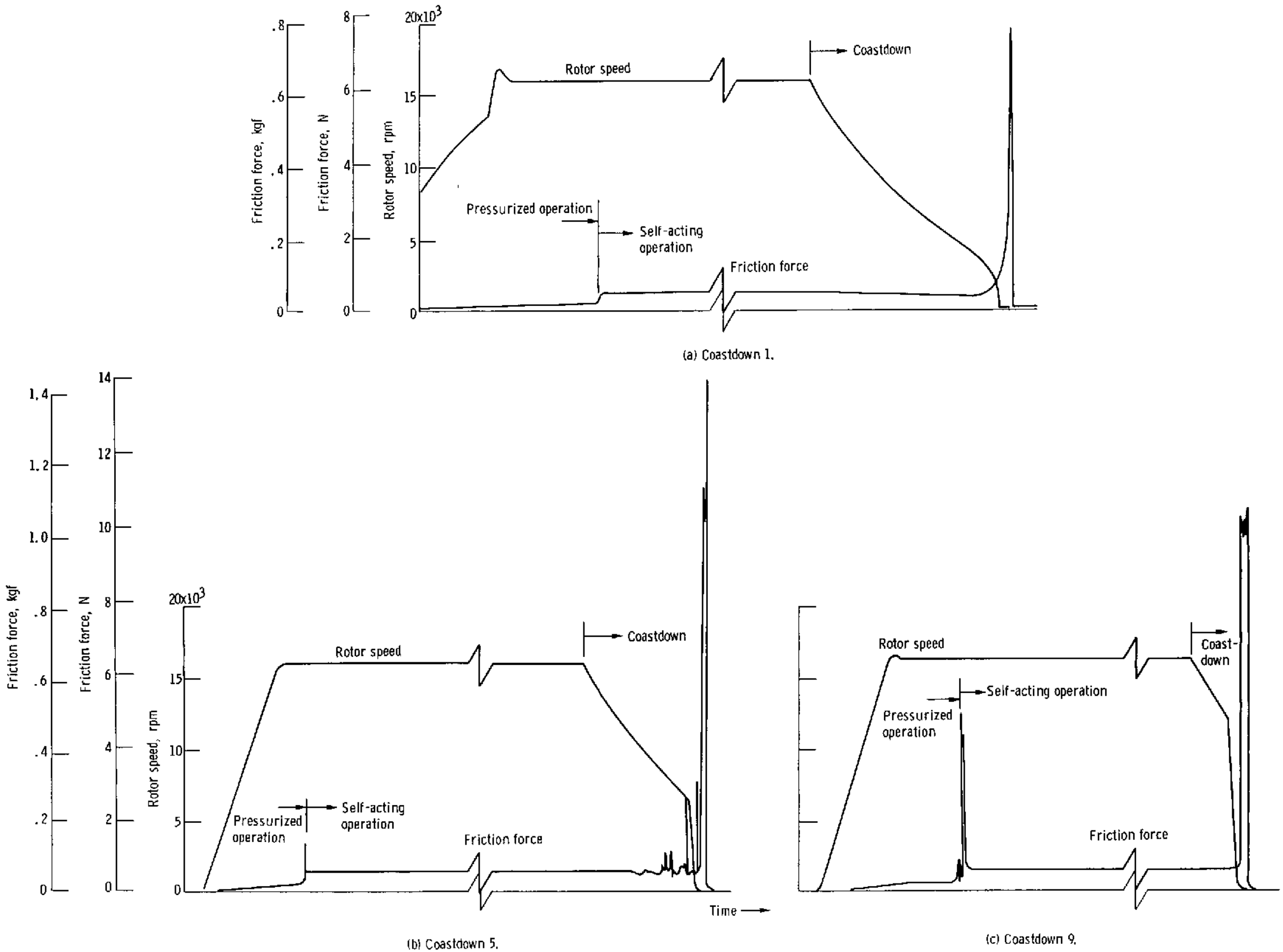


Figure 12. - Rotor speed and bearing friction for coastdowns 1, 5, and 9 of the Rayleigh step thrust bearing with MoS_2 burnished surfaces.

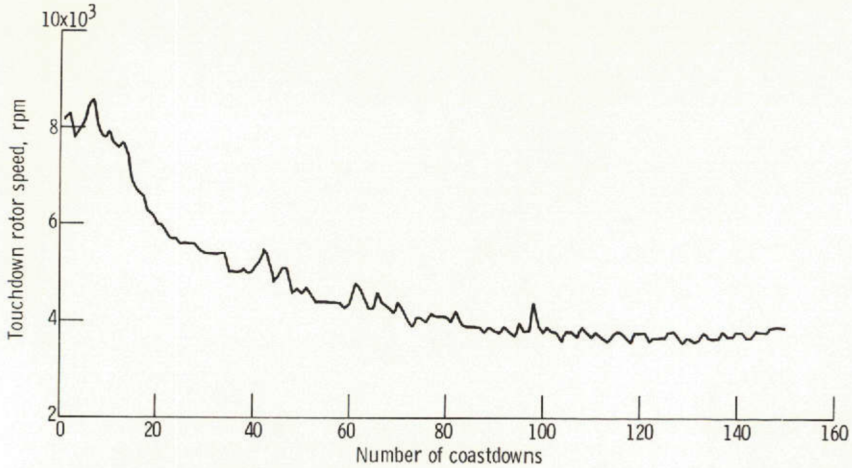


Figure 13. - Touchdown rotor speed plotted against number of coastdowns for Rayleigh step air thrust bearing. Bearing surfaces plasma spray coated Cr_2O_3.

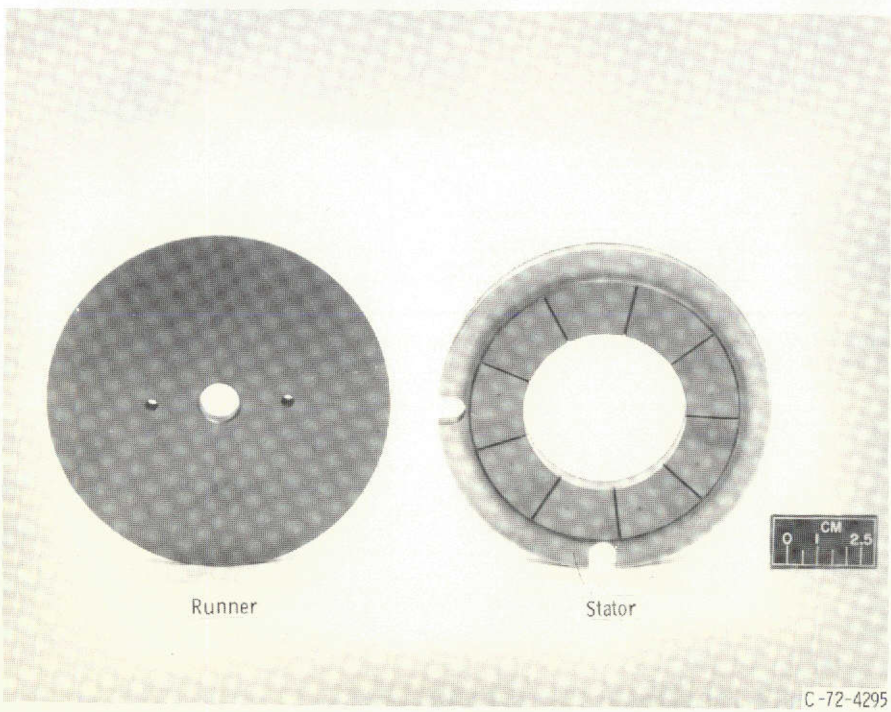


Figure 14. - Plasma sprayed Cr_2O_3 coated Rayleigh step thrust bearing stator and mating runner before test.

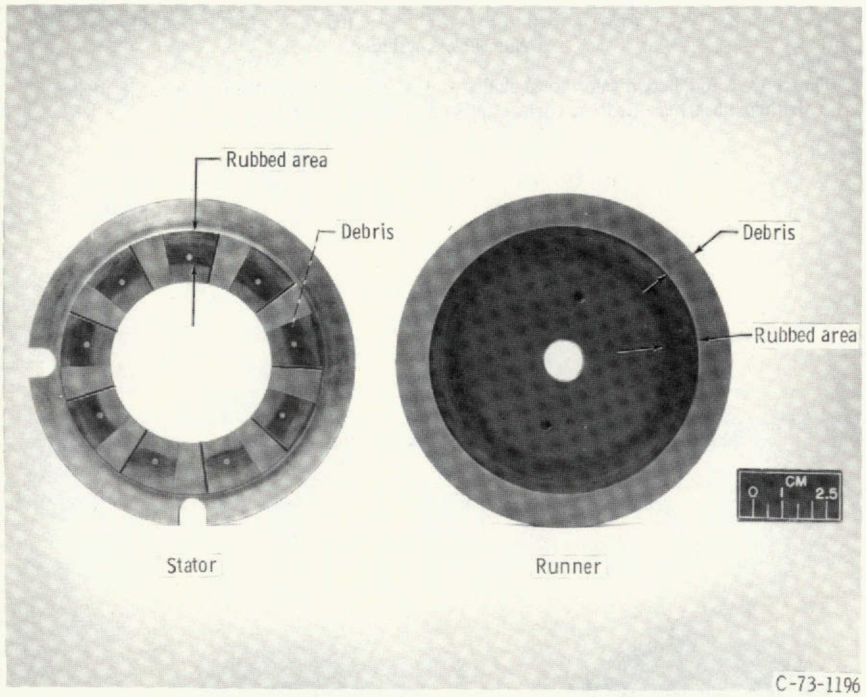


Figure 15. - Plasma sprayed Cr_2O_3 coated Rayleigh step thrust bearing stator and mating runner after 150 coastdowns.

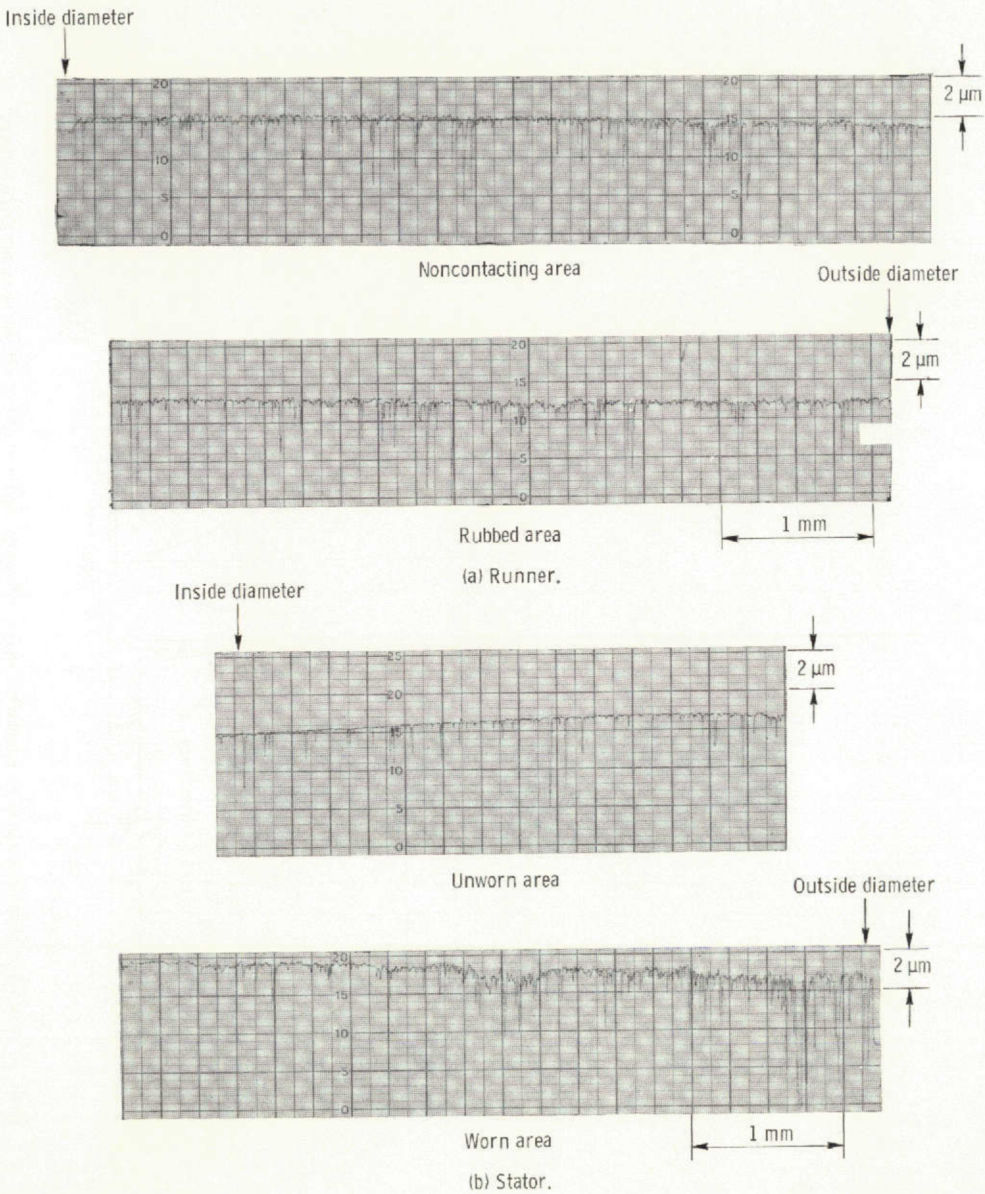
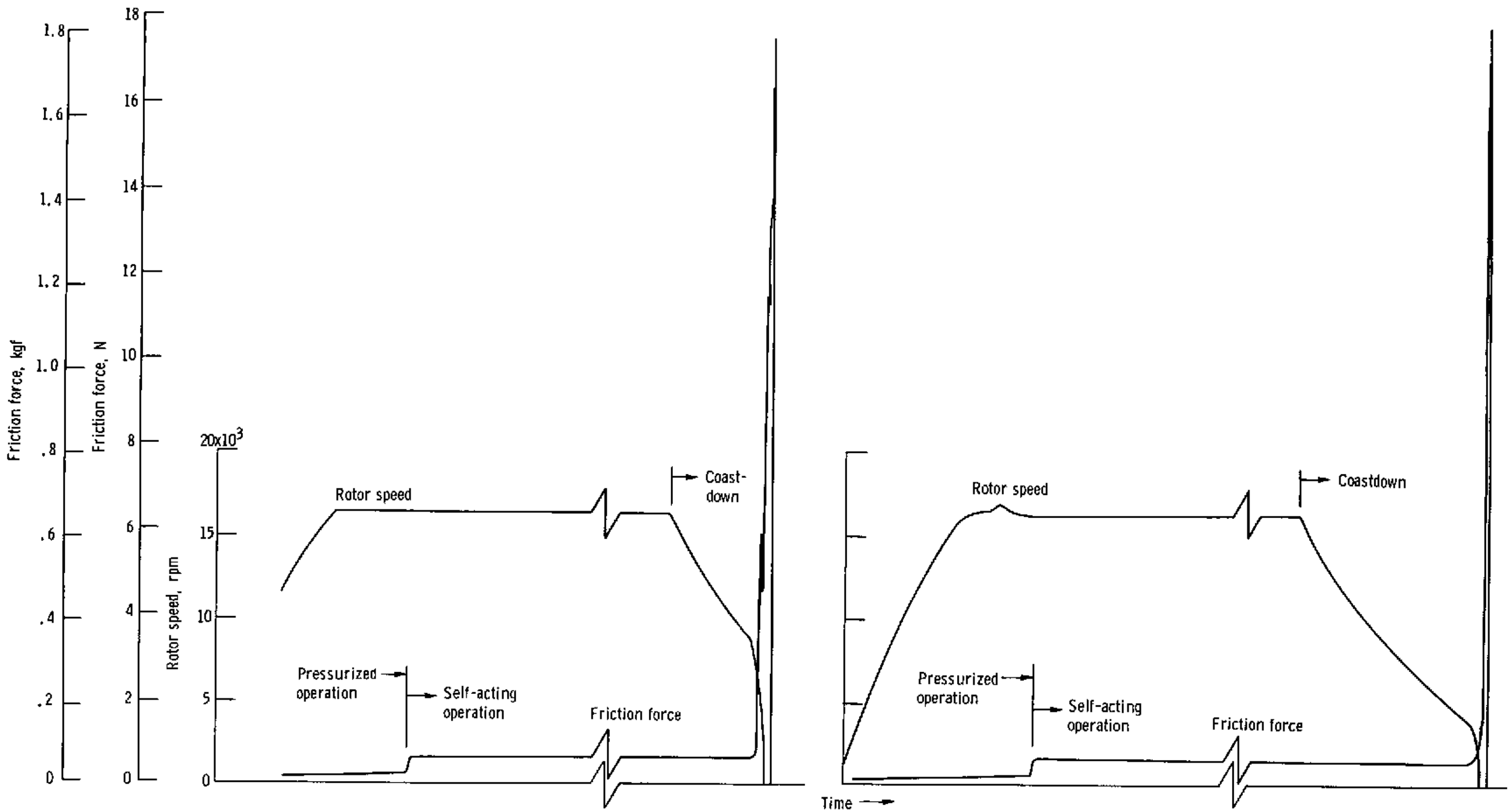


Figure 16. - Radial profile trace of plasma sprayed Cr_2O_3 coated thrust bearing stator and runner after 150 coastdowns.



(a) Coastdown 1.

(b) Coastdown 150.

Figure 17. - Rotor speed and bearing friction for coastdowns 1 and 150 of Rayleigh step thrust bearing with plasma sprayed Cr_2O_3 surfaces.

NASA-Langley, 1974 E-7777