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(NASA-CR-161672) TRANSFER FILM EVALUATION FOR SHUTTLE ENGINE TURBOPUMP BEARING Final Report (Battelle Columbus Labs., Ohio.) 23 p HC A02/MF A01 CSCL 13I

N81-20425

Unclas
G3/37 41771

Report

NAS 8-33576

FINAL REPORT

on

TRANSFER FILM EVALUATION FOR SHUTTLE ENGINE TURBOPUMP BEARING

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

by

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March 12, 1981

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INTRODUCTION

NASA is currently involved in the development and evaluation of long-life turbopumps for use on the shuttle spacecraft main engine (SSME). Because of the reusable design, lifetimes of 27,000 seconds (7.5 hours) are being sought. Since past experience with these types of turbopumps has been limited to a few hundred seconds, the shuttle pump represents a significant extension of existing technology. The mainshaft support bearings are of particular concern in this regard. Because of the high speed ($\approx$30,000 rpm) nature of the pump, the target endurance for the bearings is on the order of 1.3×10^6 revolutions.

Good ball bearing performance and life are contingent on adequate lubrication of the ball-race contact region. In conventional, liquid lubricated bearings, a thin film of lubricant is formed between ball and races, which protects them from metal-to-metal contact. In the SSME, the only liquid available is in the form of a cryogenic liquid which has, at best, questionable lubricating properties. Alternately, the bearing elements might be lubricated by Teflon transferred from the cage to the balls and to the races. Teflon-transfer-film bearings are being used in other types of applications, and it would seem that Teflon can provide some protection in the shuttle bearings.

In previous bearing evaluations at Battelle (Cf November 24, 1980 report), the as-received bearing did not exhibit any positive evidence of solid film lubrication based on high bearing friction measurements. However, when the bearing races were burnished with Teflon, the bearing friction was considerably reduced. Further, the burnished Teflon film appeared to withstand several bearing revolutions. The obvious questions then are:

(1) How many cycles can a burnished film endure?

(2) Can the transfer film mechanism be improved?

The purpose of the research reported herein has been to address the first question considering burnished film longevity, and to some extent, the second question. However, further studies are needed to address the second question concerning the enhancement of transfer mechanics.

The research reported has involved four efforts towards evaluating integrity of transfer and burnished film and overall bearing capacity. The objectives have been to:

(1) Develop a simple test fixture for checking endurance of burnished and/or transfer films.

(2) Develop a preliminary procedure for burnishing the Teflon film and evaluate burnished film longevity and bearing friction. Both Teflon and Rulon (+ 5% MoS_2) were evaluated. The Rulon was used because of the good performance known to occur with this material in other transfer film systems.

(3) Determine if transfer film mechanics occur with the existing design.

(4) Determine (experimentally) the crush-load limit for the test bearing.

SUMMARY

A series of low speed experiments to evaluate the possible occurrence of transfer film lubrication and the effectiveness of burnished films in the SSME thrust bearings were successfully conducted. In the experiments, no evidence of transfer film lubrication was evident, although this could have been the result of the (used) condition of the bearing. Burnished films of either Teflon or Rulon were found to greatly enhance the performance of the bearing. Film life on the order of 2.5×10^5 bearing revolutions for the Teflon occurred in the experiments under normal 4400 N (1,000 pounds) loading. The life was 4.3×10^5 cycles for the Rulon films. Crush load experiments indicated that the bearing ultimate load capability is on the order of 489,000 N (110,000 pounds).

Future experiments should include evaluations of the effect of ball (as well as race) burnishing techniques on bearing performance. In addition, different types of burnished films should be evaluated. Finally, more experiments on transfer film formation should be conducted. These transfer film studies should include experiments with new (as opposed to used) bearings and experiments with techniques to enhance transfer film formations.

PROJECT DETAILS

Apparatus for Burnished Film Experiments

The objective of the bearing experiments was to determine the number of cycles a burnished or transfer film could sustain under high load conditions. In order to meet this objective within limited time and budget constraints, extreme simplicity was required of the experimental apparatus. The device chosen involved the simple two bearing device illustrated in Figure 1.

The lower (slave) bearing in the apparatus is a grease lubricated bearing and serves to balance the thrust load on the test bearing. A solid plate separates the slave bearing from the test (solid lubricated)

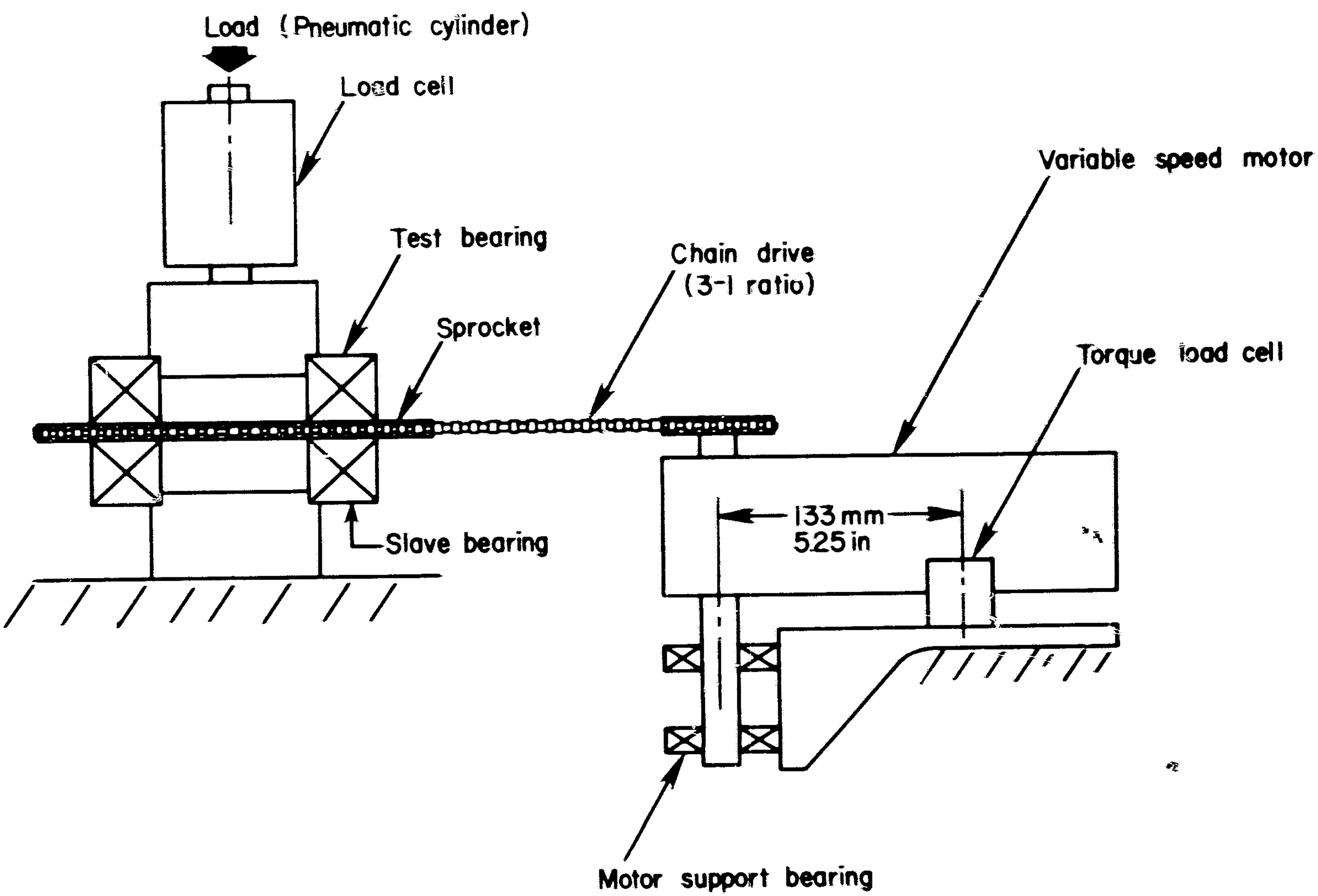

FIGURE 1. SCHEMATIC DIAGRAM OF APPARATUS

bearing. This plate contains a 48 tooth sprocket used to rotate the bearings. The test bearing is loaded by means of a pneumatic cylinder arrangement having a capacity of at least 89,000 N (20,000 pounds) axial load. The bearing load is monitored by means of a load cell situated between the bearing and the cylinder.

The drive motor in the apparatus is a 1 horsepower, variable speed unit and is coupled by means of a chain sprocket (3-1 step down) arrangement to the bearing set; normal bearing speed was 88 rpm. The drive motor is mounted on a pair of "motor-support bearings". This mounting arrangement allows for the motor to move freely about its sprocket center-line. The only pivotal constraint on the motor mount is a load cell located 133 mm (5.25 inches) from the free pivot. This load cell detects the torque originating from the thrust and slave bearing combinations.

The output from the load cells detecting bearing load and bearing torque were continuously monitored by a two-channel strip-chart recorder. An automatic shut-off system was used to terminate the experiments if the torque level exceeded a preset level. This automatic shut-off arrangement allowed for long duration (overnight) experiments to be conducted with the apparatus.

A photograph of the apparatus and instrumentation is shown in Figure 2. The main frame and pneumatic loading arrangement are a commercial (Dake) unit which was available at Battelle. The primary instrumentation consisted of two strain-gage amplifiers and the two-channel recorder system.

Experimental Procedures

Bearing Torque Calibration

The bearing torque measurement technique is quite simple and reliable. Unfortunately, it monitors the torque from both the slave as well as the test bearings. To calibrate for the test bearing torque, a third (dummy) bearing technique was utilized. This technique involved

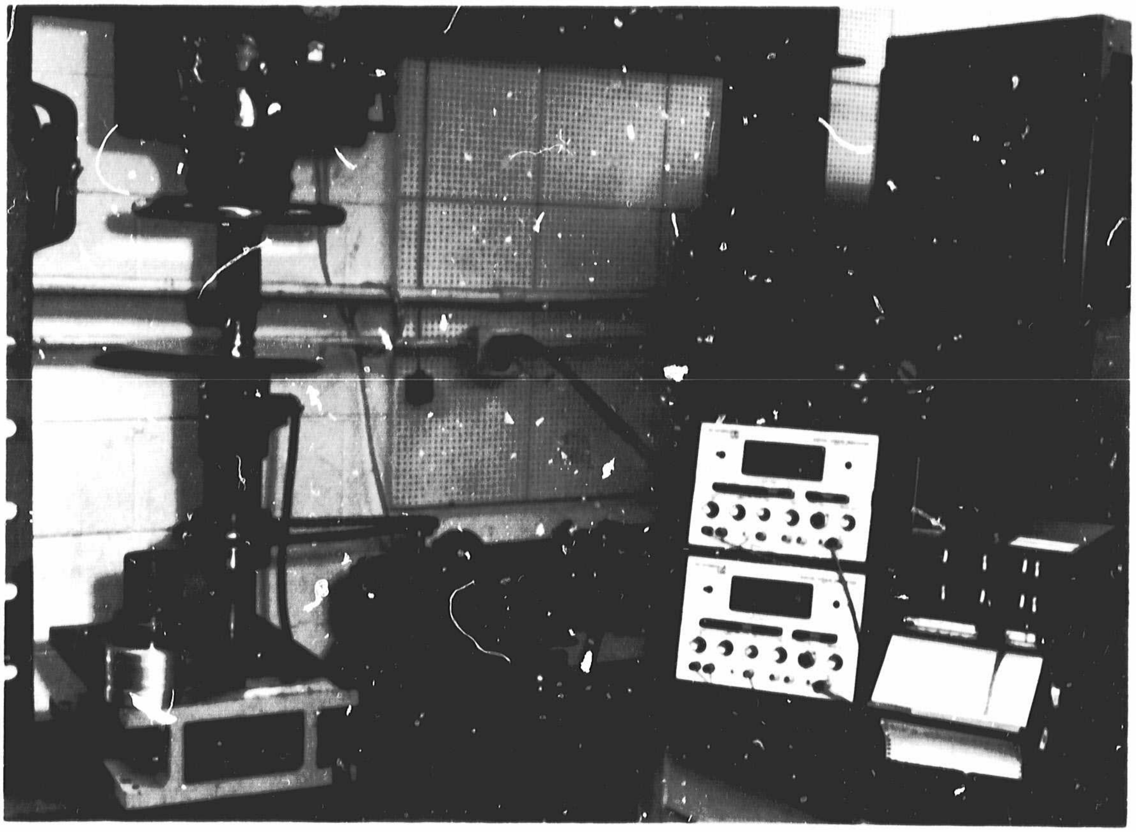

FIGURE 2. PHOTOGRAPH OF BEARING APPARATUS

conducting experiments for three combinations of bearings for various load conditions, as follows:

(1) Test bearing and slave bearing.

(2) Test bearing and dummy bearing.

(3) Dummy bearing and slave bearing.

From the results of these experiments, a base line torque factor for the slave bearing was developed.

Bearing Burnishing Technique

The goal of the burnishing of the bearing is to coat the maximum amount and the most durable layer of Teflon on the bearing elements as is feasible. The initial trials involved coating only the bearing races. However, the early experiments indicated that race coatings alone would not produce the desired life for the bearing. It was found that even a meager coating on the balls enhanced life significantly. Much more work is needed in the area of ball burnishing to optimize performance.

The procedure used for the bearing burnishing is as follows:

(1) The bearing balls and races were cleaned in a commercial (SWECO) bearing grit-cleaning device. This operation removes any previous films on the bearings and provides a fresh surface for the burnishing process.

(2) The balls and races are wiped dry and cleaned with standard methanol.

(3) The bearing balls are put in a 2-inch (50 mm) diameter glass jar containing Teflon powder and tumbled for 2 hours. (This procedure coats a thin film on the balls, but is by no means an optimum method for coating the balls.)

(4) The races are mounted in a commercial lathe and turned at a speed of 600 rpm at room temperature. A Teflon block is loaded against the races with a force of 44-66 N (10-15 pounds) for a period of 10-15 minutes. The time period is based on visual observation of the coated film.

(5) The bearing is reassembled and mounted in the test apparatus.

The same procedure was used for coating the bearing races with Rulon (+ 5% MoS_2), except that 5% MoS_2 was added to the Teflon powder for the ball tumbling operations.

Nonburnished Bearing Experiments

All of the experiments were conducted using the same bearing. This bearing had been removed from a successful engine firing test and was in very good condition. This bearing (designated 7955) is a 440 C angular contact used as the thrust bearing for the SSME high-pressure liquid-oxygen turbopump. Some general data on the bearing is given in Table 1 for reference purposes. In all experiments, the bearing was precleaned by the procedure outlined in the previous section.

The initial experiments were conducted with nonburnished balls and races to determine base line (dry) friction and to evaluate the propensity for transfer-film development under high load conditions. In these initial experiments, there was considerable wear of the balls and races, as evidenced by metallic debris around the apparatus. Also, there was notable cage wear, but there was no evidence of Teflon transfer from the cage to the balls, even after many hundreds of revolutions. This lack of Teflon transfer is disconcerting because it suggests that transfer-film lubrication with the current cage design may not be viable for this bearing. It can be conjectured that the available Teflon at the ball pockets had worn away during the previous engine test with this bearing, which left only glass fibers exposed to cage surfaces. Considerably more work is needed here involving new bearings and/or ball pockets designed to promote transfer film lubrication.

In all of the experiments, the sequence was terminated when a significant increase in torque occurred. Table 2 shows typical starting and termination torques from the experiments, along with the test duration. The nonburnished bearing experiments are designated by sequence numbers D-1 to D-5. The initial torques were on the order of 27 in/lb (3 N-m) for the 2,000 pound (8,900 N) experiment and increased to 180 in/lb (20 N-m) at the highest 10,000 pound (44,000 N) load. The

TABLE 1. ASSUMED BEARING DESIGN CONDITIONS

Parameter		Bearing Type 7955
Ball Diameter	m(in)	.012 (.500)
Pitch Diameter	m(in)	.081 (3.19)
Contact Angle	Degrees	20.5
Inner Race Curvature		.53
Outer Race Curvature		.53
Number of Balls		13
Speed	RPM	30,000

TABLE 2. SUMMARY OF BURNISHED FILM PERFORMANCE

Sequence Number	Lubricant (Preburnished)	Load N (lbs)	Torque Running N-m (in/lb)	Torque Terminal N-m (in/lb)	Duration 10^4 Revolutions
D-1	None	8,900 (2,000)	3. (27)	6. (57)	.075
D-2	None	17,800 (4,000)	10. (90)	19. (120)	.03
D-3	None	27,000 (6,000)	17. (150)	19. (165)	.026
D-4	None	36,000 (8,000)	19. (165)	24 (210)	.026
D-5	None	44,000 (10,000)	20. (180)	25. (225)	.05
T-1	Teflon	4,400 (1,000)	1. (9.5)	1.5 (13)	27.
T-2	Teflon	4,400 (1,000)	1.1 (10.2)	2.2 (20)	25.
T-3	Teflon	8,900 (2,000)	1.8 (16)	4.5 (40)	13.
T-4	Teflon	17,800 (4,000)	2.8 (25)	3.4 (30)	4.2
T-5	Teflon	53,000 (12,000)	8.3 (73)	10.2 (90)	.48
T-6	Teflon	62,000 (14,000)	10. (88)	11. (100)	.53
R-1	Rulon	4,400 (1,000)	1.1 (10.2)	2.8 (24)	43.
R-2	+5% MoS_2	8,900 (2,000)	1.9 (17)	4.9 (40)	1.7
R-3	"	17,800.(4,000)	3.2 (28)	5.7 (50)	3.6
R-4	"	36,000 (8,000)	5.8 (51)	8.3 (73)	1.1
R-5	"	53,000 (12,000)	8.0 (71)	9.4 (83)	.44
R-6	"	62,000 (14,000)	8.8 (78)	9.9 (88)	.18

terminal (shut-down) torques were chosen to be about 3.5 N-m (27-45 in/lb) increase over the initial torques.

In general, the nonburnished bearings performed badly. As mentioned earlier, metallic wear debris was released from the bearing, and the bearing survived for only a relatively few revolutions before a torque increase occurred.

Burnished Bearing Experiments

A summary of the experiments involving burnished balls and races is also given in Table 2. Sequences T-1 to T-6 pertain to the burnished Teflon experiments, and sequences R-1 to R-6 pertain to the Rulon tests. In all cases, the torques associated with the burnished films were considerably less than those associated with "clean" bearings (D-1 to D-5). For example, a bearing with Teflon film produced a torque of about 1.8 N-m (16 in/lb) at 8,900 N (2,000 pounds) axial load, where as the "clean" bearing produced a torque of 3 N-m (27 in/lb) for the same load. In this regard, the torque associated with the Rulon film is 1.9 N-m (17 in/lb), which is quite similar to the Teflon. Figure 3 summarizes the torque data for the two transfer film lubricants as a function of load.

The primary concern for the bearings in the regard of the space shuttle is the operating life. Past evaluations of full engine test bearings have revealed that several bearings have failed in a relatively short time period. The goal of the burnished film experiments has been to determine if an increase in life will occur as a result of this burnishing. Table 2 shows performance life data for various load conditions. At a load of 4,400 N (1,000 pounds), the Teflon film incurred 2.5-2.7 x 10^5 revolutions before a torque increase occurred. This would be equivalent to the number of cycles an engine bearing operating at 30,000 rpm would incur in 500 seconds ($\sim$1 launch). The Rulon film endured almost twice as many cycles at the same load, or the equivalent to two launch cycles.

Even at increased loading, the burnished film endured a significant number of cycles. For example, the Rulon film withstood 1.1 x 10^4 revolutions even at 35,600 N (8,000 pounds) load. This implies that burnished

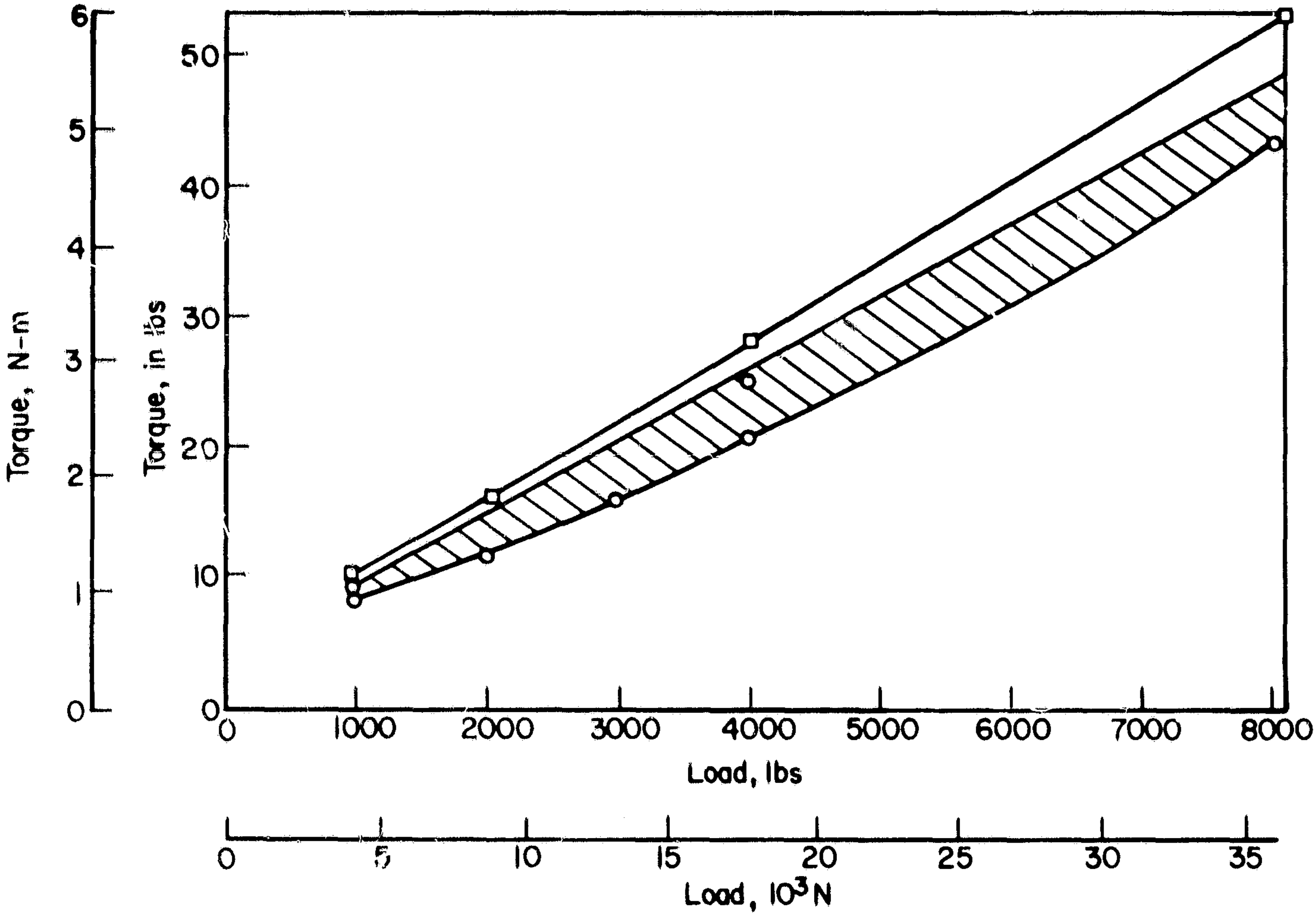

FIGURE 3. TORQUE LOAD CURVE FOR A SINGLE BEARING

films can, at least, assist the engine bearings during short-duration overloading. A summary of the duration of the films is given in Figure 4.

Although significant life can be expected at higher loaded conditions, the life is considerably less than would occur for the 4,400 N (1,000 pounds) load. One explanation for the loss of life with load is shown in Figure 5. Transfer films appear to have some upper limit of stress capacity. This limit is about 2 GPa (300,000 psi). The shuttle bearings incur this stress at a load of 4,400 N (1,000 pounds). Loads in excess of this level produce stresses which are, at best, marginal for transfer film integrity.

An alternate method for evaluating transfer or burnished film behavior is to monitor the electrical insulation capability of the films. In the course of the longer duration experiments (T-2 and R-1), random monitoring of resistance was made by means of a commercial resistance meter. The results are presented in Figure 6. In both cases shown, a high resistance (>50,000 Ω) was developed early in the experiment, which is indicative of good layers of Teflon or Rulon throughout the bearing. At the time of film failure, the resistance became very small. This measurement simply further illustrated that the burnished film had either been destroyed or consumed at the ball-race contacts in the bearing.

Extension to Shuttle Engine

The goal of the burnished film experiment was to evaluate the life of surface films under shuttle engine load conditions. No effort was made to duplicate the cryogenic environment or speed-related parameters. The good results indicate that burnished films can potentially greatly assist the shuttle system for a range of anticipated load conditions. Actually, as shown in Figure 5, the maximum stress in the bearing at low rpm was probably greater for the experiment than for the actual engine at 30,000 rpm. That is, although centrifugal forces increase outer race stress, they reduce the inner race stress. Since at low speed, inner race stresses are always the dominant in the bearing, the peak stresses

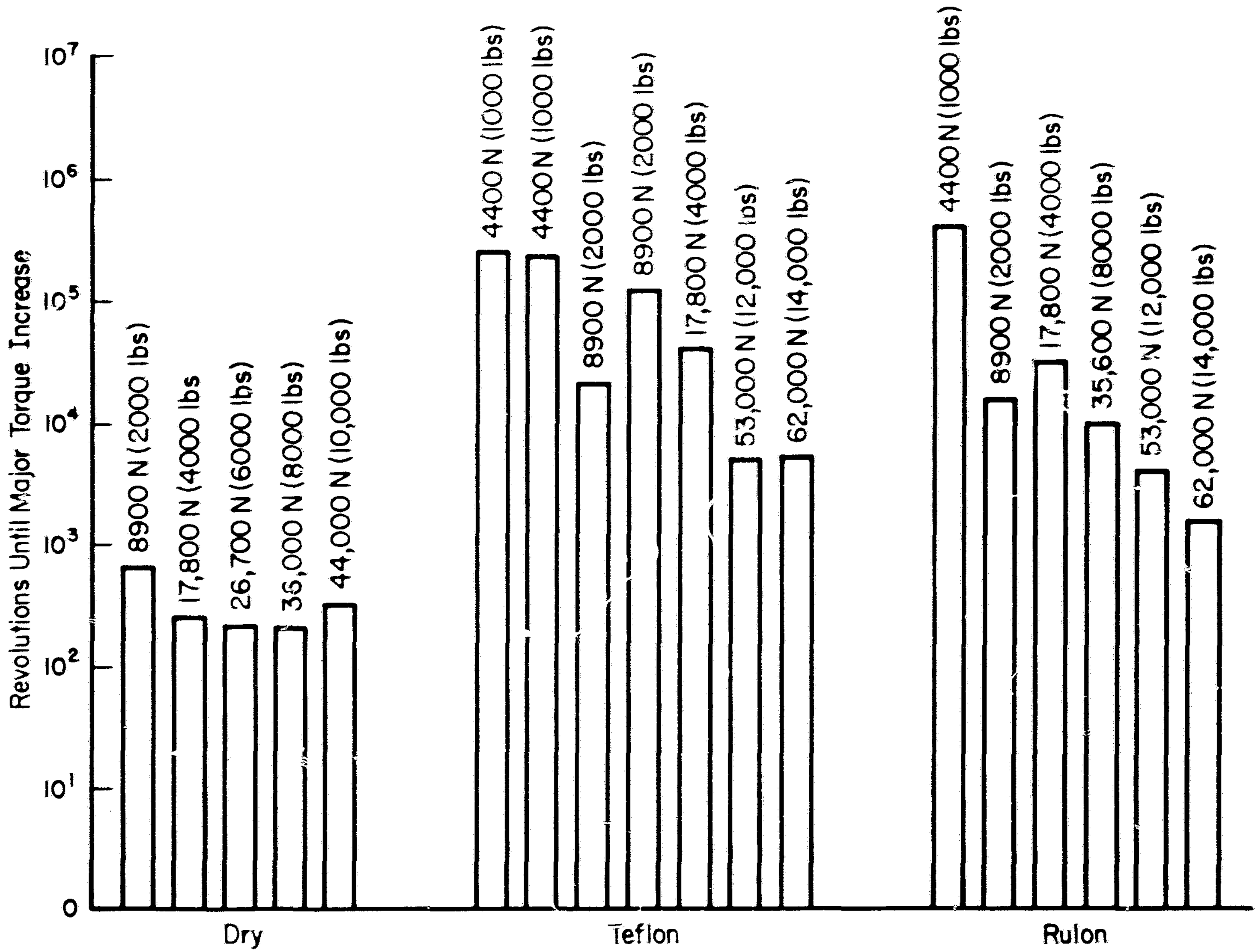

FIGURE 4. SUMMARY OF DURATION OF BURNISHED FILMS

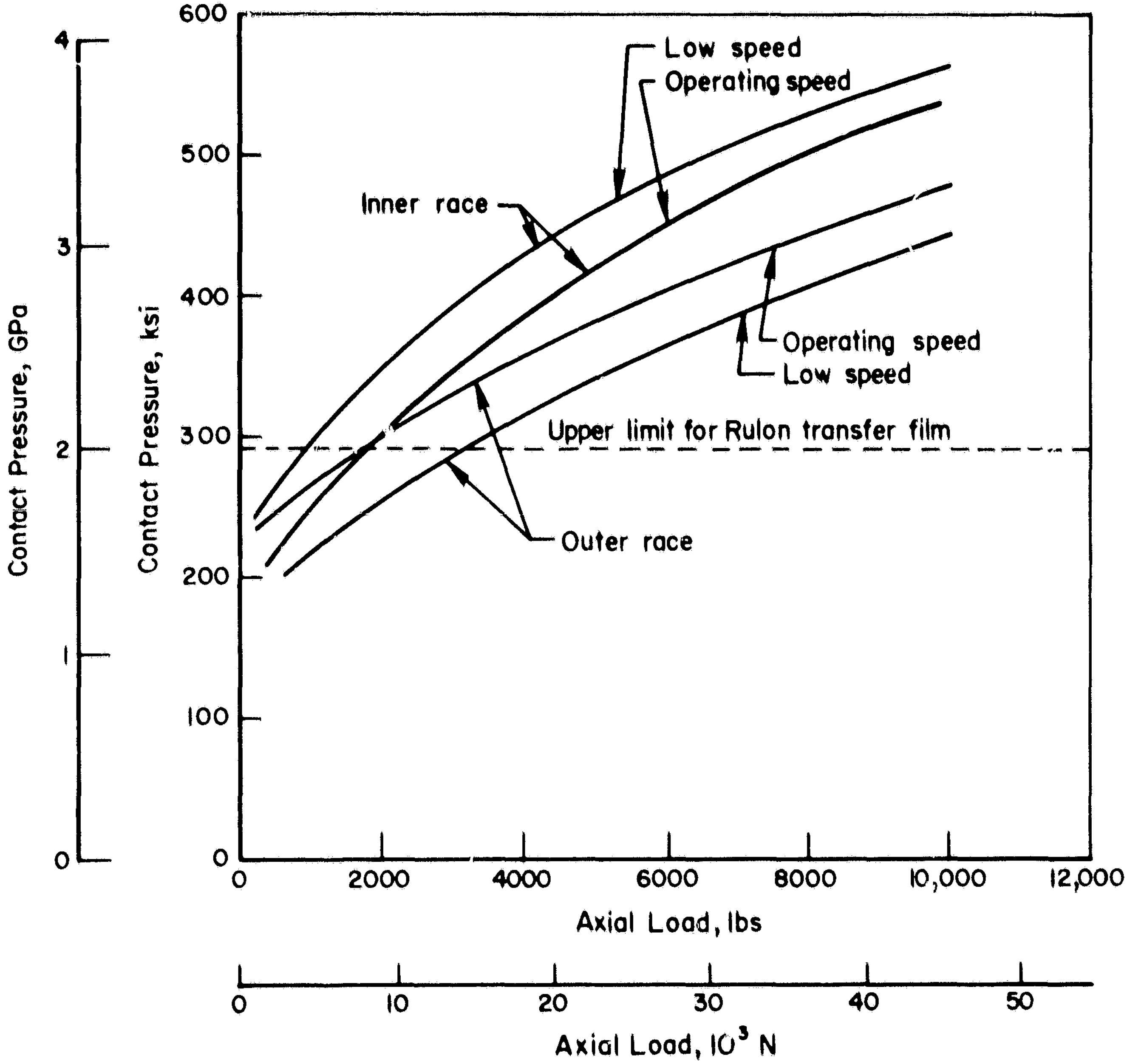

FIGURE 5. EFFECT OF AXIAL LOAD ON BEARING STRESS

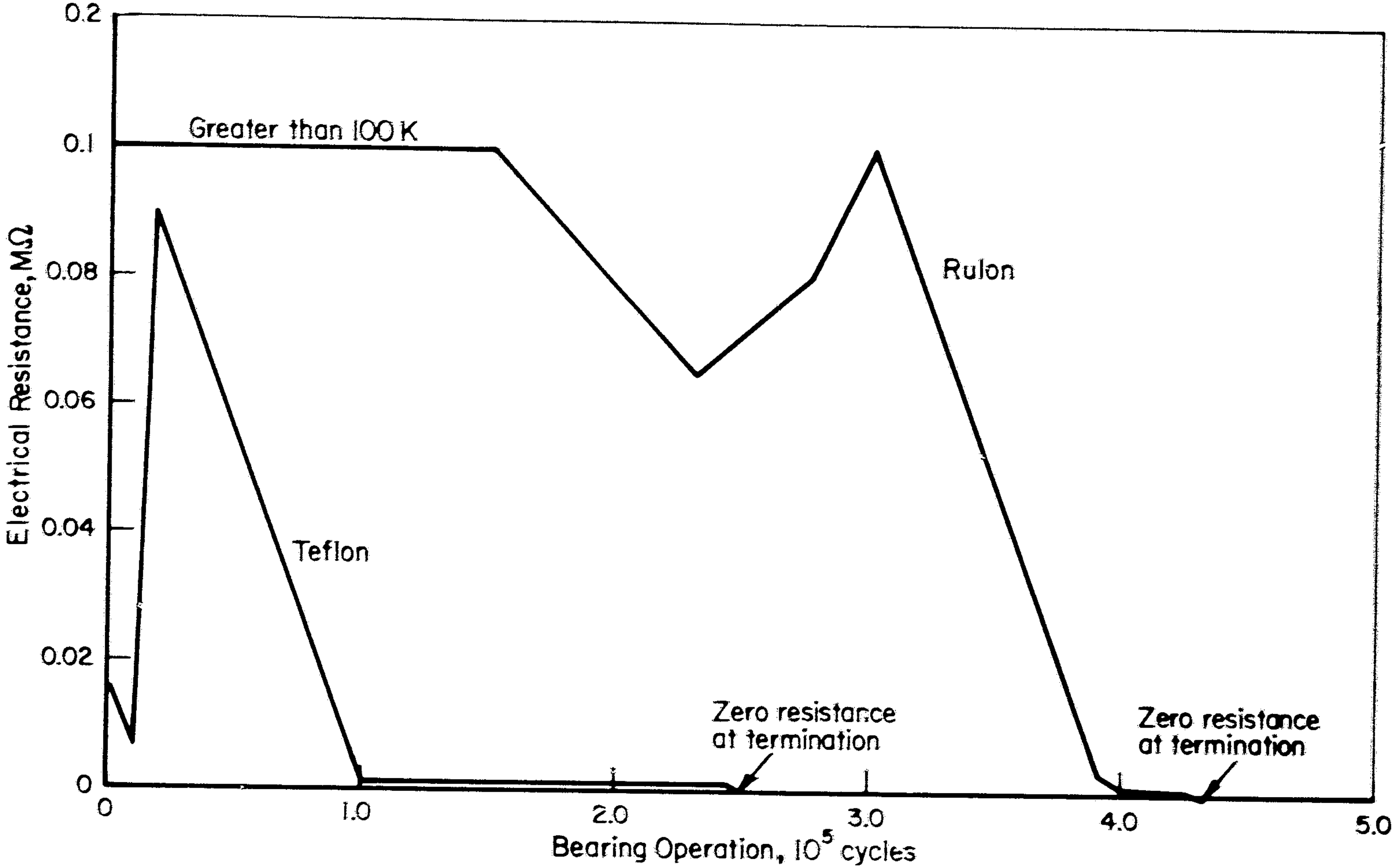

FIGURE 6. CONTACT RESISTANCE HISTORY FOR BEARING OPERATING WITH 4400 N (1,000 POUNDS) LOAD

at low speeds may be higher than the peak stresses at high speeds. Of course, this evaluation does not include dynamic radial-load effects.

In general, the data given here offers sufficient evidence that burnished films can assist the engine operation to merit full scale tests. Further work is needed, however, in the area of ball burnishing. It should be noted that the surface area of the balls is greater than the ball tracks on the races at a given load-speed condition. It is possible, then, that better ball burnishing can yield more film surface area to the bearing and can lead to even better performance life than measured in the low speed tests.

Crush Load Tests

A final test in the project was to determine the crush load of the bearing. For this experiment, a special housing was fabricated to contain the bearing outer race. The diametral clearance between the outer race and this housing was approximately 0.05 m (0.002 inch). The assembly was loaded in a universal testing machine with ultimate capacity in excess of 890,000 N (200,000 pounds). A load-deflection curve was developed by this machine in the course of the experiment, as shown in Figure 7. At a load of 489,000 N (110,000 pounds), the bearing emitted audible fracture sounds, which were accompanied by instantaneous increases in deflection. In our earlier report (Kannel and Merriman, August, 1980), it was predicted that the 7955 bearing would crush at loads on the order of 480,000 N (108,000 pounds). The measured fracture load is consistant with those predictions.

A photograph of the bearing (including the outer race containment system) is given in Figure 8. At the severe loading imposed in the experiment, gross plastic flow of the races and balls occurred. Also, the outer race was fractured under each ball location and 4 balls were fractured.

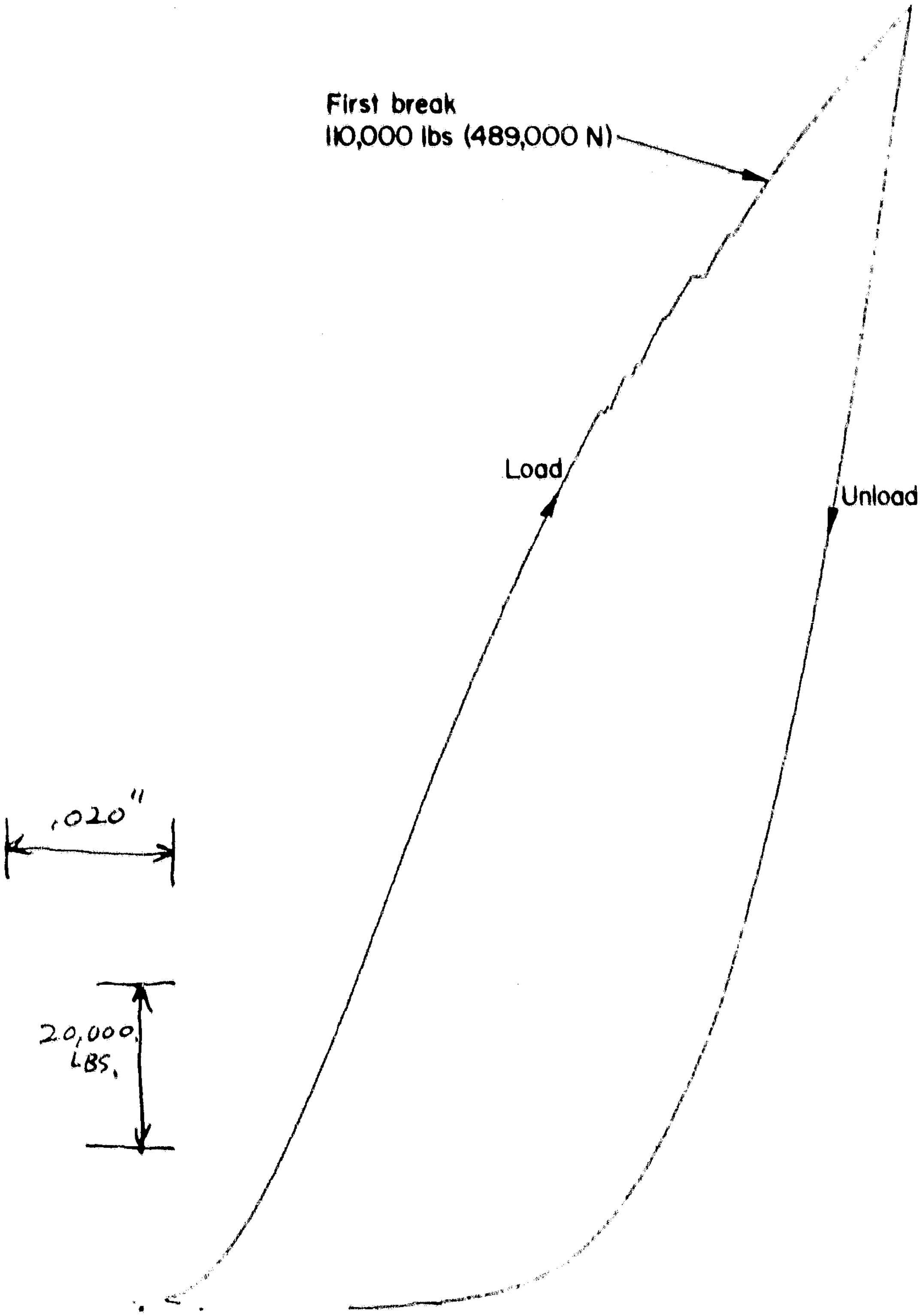

FIGURE 7. CRUSH LOAD TEST WITH 7955 BEARING

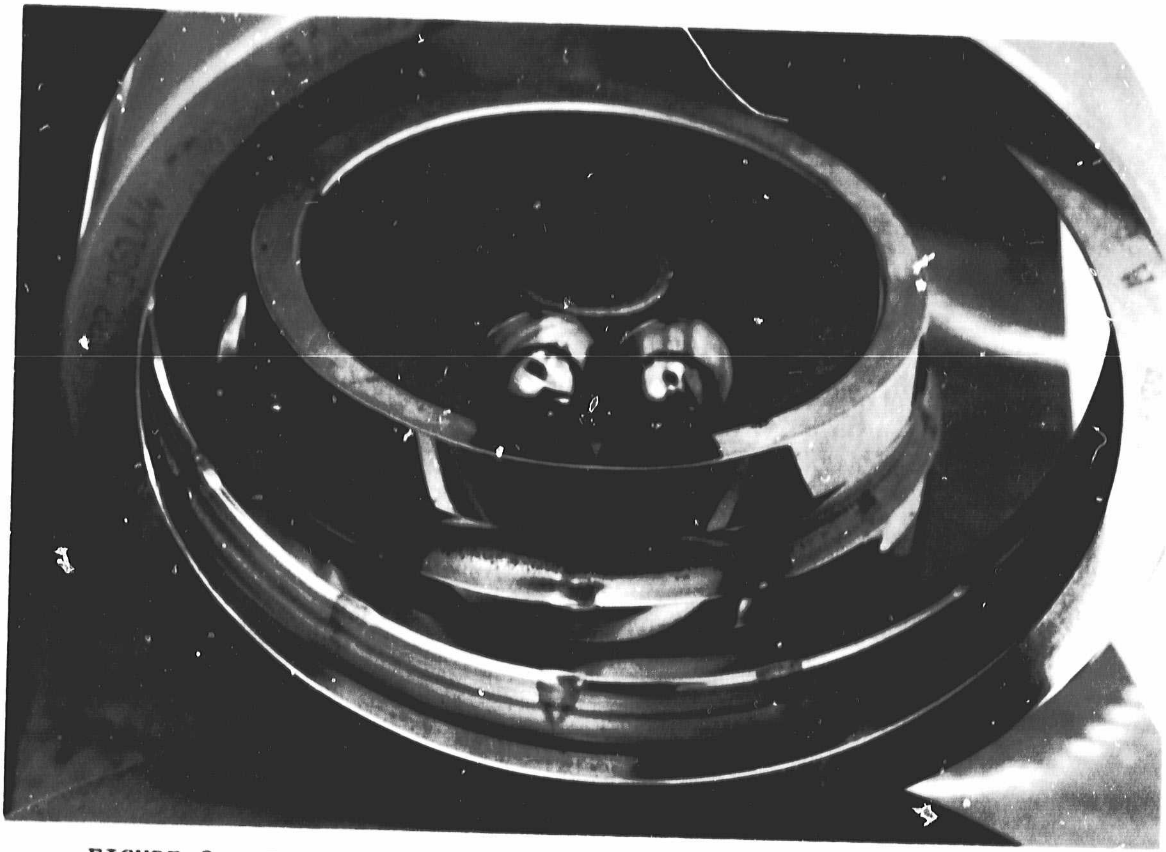

FIGURE 8. PHOTOGRAPH OF 7955 BEARING AFTER CRUSHING EXPERIMENT

Calculating Units

Since the bearing drawing and all input data provided by NASA were in English units, all calculations were performed in English units. Therefore, the SI units presented in this report were converted from English units. The data on which this report is based is located in Battelle Laboratory Record Book Number 34405.