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STUDIES OF ROLLING-ELEMENT LUBRICATION AND FATIGUE LIFE IN A REDUCED PRESSURE ENVIRONMENT

by David W. Reichard, Richard J. Parker and Erwin V. Zaretsky

Lewis Research Center
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TECHNICAL PAPER proposed for presentation at
Anual Meeting of the American Society of Lubrication
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ABSTRACT

Fatigue tests were conducted in a modified five-ball fatigue tester on SAE 52100 steel ball specimens, at atmospheric pressure and at the approximate lubricant vapor pressure with two different lubrication methods, using a super-refined naphthenic mineral oil as the lubricant. Additional tests were conducted with AISI M-50 ball specimens with polyphenyl ether lubricants. Differences in fatigue life, deformation and wear with the mineral oil lubricant were insignificant regardless of the ambient pressure environment or lubrication method employed. Polyphenyl ether lubricants exhibited large amounts of wear both at atmospheric and reduced pressures indicating a lack of an elastohydrodynamic film with this lubricant under the stresses and sliding velocities present in the five-ball fatigue tester.

INTRODUCTION

In many aerospace applications rolling-element bearings are utilized in semi-sealed systems having an environmental pressure equal to that of the lubricant vapor pressure. Problems which might be encountered in such a reduced pressure environment are: (a) evaporation of the lubricating fluid, limiting the useful time the bearing can be operated and (b) the removal of surface oxide films by wear more rapidly then they can be replaced. Where elastohydrodynamic conditions exist, complete separation of the rolling-element surfaces is accomplished, therefore surface oxides are of small importance in inhibiting rolling-element wear for long term operation. In addition with properly designed static and dynamic seals lubricant evaporation can be reduced to a negligible amount for extended operation.

Rolling-element fatigue life is affected by lubricant viscosity. In general, as lubricant viscosity increases, so does the fatigue life of a rolling-element bearing.[1] Decreases in apparent bulk viscosity of a super-refined mineral oil and an ester based oil were obtained by saturating the lubricating fluid with nitrogen gas (2). Conversely exposing the lubricating fluid to a reduced pressure environment can increase the bulk viscosity by degassing the lubricant.

Among the most often considered lubricants for bearings, gears, and hydraulic systems in applications where high thermal and oxidative stability and resistance to nuclear radiation are necessary are the polyphenyl ethers. Because the polyphenyl ethers have these desirable properties along with relatively low vapor pressures, they are being considered as the lubricant in a closed organic lubrication loop in space power generation systems such as Snap-8. In such a system, the lubricant would be exposed to pressures less than atmospheric. Additionally, the bearings would be exposed to approximately a 300 F temperature and made from AISI M-50 steel.

The objectives of the research described herein, which is based upon the work reported initially in (3), were to determine: (a) if there is a relation between ambient pressure and fatigue life; (b) if, under reduced pressure conditions, rolling-element fatigue life is different with quasi-mist (partially flashing of the lubricant upon exposure to the reduced pressure) lubrication and total immersion of the rolling elements in the lubricant; and (c) if differences exist in deformation and wear of rolling-elements run under normal atmospheric conditions and in a reduced pressure environment with a mineral oil and a polyphenyl ether as a lubricant. All experimental results were obtained with the same heat of material and lubricant batch except where indicated.

APPARATUS

The NASA five-ball fatigue tester, modified for reduced pressure testing, was used for this investigation. The modified five-ball apparatus has been previously described in (3) and is shown in Fig. 1a. Figure 1b is the apparatus before modification. Briefly, it comprises an upper test ball pyramided on four lower support balls which are positioned by a separator and are free to rotate in an angular-contact raceway (Fig. 1c). System loading and drive are supplied through a vertical drive shaft. Failure detection instrumentation was provided permitting long term unmonitored tests.

The apparatus modification comprises access tubes to the test chamber for a vacuum pumping system and its accompanying pressure monitoring instrumentation, and a mechanical shaft seal of the spring-loaded, carbon-face type. The seal was lubricated and cooled with the test lubricant. Its performance at 4900 RPM was such that no leaks could be detected with a helium leak detector.

The vacuum pumping system was a commercial system capable of attaining pressures of 10^{-6} Torr (mm Hg). It comprises a mechanical fore-pump and a 2-inch oil diffusion pump with a liquid nitrogen cold trap. An automatic liquid nitrogen dispensing system was provided making possible the necessary long term tests. A schematic of the vacuum system is shown in Fig. 2.

Test lubricant was supplied to the test chamber from a reservoir under a nitrogen gas cover. The gage pressure in the reservoir was maintained at 2 to 3 inches of water. The lubricant flow rate to the test assembly was controlled by an adjustable needle valve.

Procedure and Materials

Fatigue tests were conducted with one-half inch diameter SAE 52100 steel balls of nominal Rockwell C hardness 62.5 as upper and lower test balls in the NASA five-ball fatigue tester. All balls were from the same heat of material. The lower balls were positioned in a raceway having a 20° contact angle. Test conditions under an atmospheric environment were a thrust load of 60 pounds which produced a maximum Hertz stress of 800 000 psi in the upper-lower ball contact, a speed of 4900 rpm, and no heat added. A super-refined naphthenic mineral oil was used as the test lubricant. Table 1 lists the properties of this lubricant.

At the completion of the fatigue tests under the atmospheric pressure conditions, tests were run at reduced pressure under the same test conditions. Prior to starting a test, the test chamber was pumped down to approximately 10^{-6} Torr and lubricant was allowed to enter the chamber. Due to the reduced pressure the lubricant became a quasi-mist and the pressure in the chamber was approximately that of the vapor pressure of the lubricant. Lubricant flow rate was the same as that of the atmospheric environment tests which provided adequate elastohydrodynamic lubrication.

A second series of reduced pressure environment fatigue tests were conducted under an immersed lubrication condition. In this series of tests all test conditions and procedures were the same as previously described with the exception that the lubricant drainage was modified such that the test assembly was immersed in the lubricant. The pressure in the test chamber was approximately that of the lubricant vapor pressure.

Rolling-element fatigue tests were conducted with a 5P4E polyphenyl ether lubricant in the five-ball fatigue tester shown in Fig. 1b. Tests were run with ball specimens of M-50 steel of a nominal Rockwell C hardness of 64, a contact angle of 30°, and a race temperature of 300 F. Initial tests were run at a maximum Hertz stress of 800 000 psi. Rolling-element studies were also conducted with a 4P3E polyphenyl ether in the modified five-ball tester (Fig. 1a). Tests were run at atmospheric pressure and at reduced pressure with AISI M-50 balls at 300 F race temperature.

Profile traces of the test specimen running tracks were made to determine if there was an effect of the reduced pressure and lubrication method on rolling element geometry. The effects manifest themselves by an alteration of the rolling-element surfaces. This alteration takes three basic forms: (a) elastic deformation; (b) plastic deformation; and (c) wear. The latter two forms result in permanent alteration of the ball surface contour that can be measured after testing. Figure 3 is a schematic diagram of the transverse section of a ball surface showing these permanent alteration forms.

RESULTS AND DISCUSSION

Fatigue Life Results

Results of the fatigue tests are presented in the Weibull plots of Fig. 4. The fatigue data were analyzed according to the statistical methods of (4). For applications where high reliability is of paramount importance, early failure of bearings is of primary interest. Hence, the significant life on a Weibull plot is the ten-percent life. A summary of these fatigue data is presented in Table 2.

Effect of Reduced Pressure on Fatigue Life

Research reported in (2) has indicated that for a super-refined mineral oil of the type used in the tests reported herein, an approximate 50 percent decrease in viscosity can occur by saturating the fluid with nitrogen gas.

Conversely, a two to one increase in apparent bulk viscosity can occur by degassing the lubricant. For the atmospheric pressure tests the lubricant was introduced into an air environment. Additionally, the lubricant was used as obtained from the manufacturer. Experience has shown that a fluid in this condition can be highly saturated with air. For the reduced pressure tests, the fluid was degassed prior to usage. In addition, any entrapped gases would have a tendency to be eliminated when the lubricant enters the reduced pressure of the test chamber. Therefore, for purposes of example, it was assumed that the fluid used in the reduced pressure tests may have had an apparent viscosity of twice that used for the atmospheric tests. Investigators have shown that, as the viscosity at atmospheric pressure of a mineral oil lubricant is increased, the life of a rolling-element also increases (3, 5). The accepted relation between life L and lubricant viscosity μ is $L = K\mu^n$ where K is a constant and n equals 0.2 to 0.3 (3, 4). Therefore, if n is taken as 0.25, life would be expected to increase by approximately 19 percent based upon a two-to-one increase in viscosity. From Fig. 4d and Table 1, the ten-percent life with quasi-mist lubrication at reduced pressure indicated approximately an increase in life of 47 percent over that with the atmospheric pressure tests. However, the immersed-lubrication reduced pressure tests indicate a reduction in life of approximately 23 percent. Therefore, in order to come to any conclusions regarding these results the data must be approached from a statistical basis.

The confidence that can be placed in the experimental results was determined statistically using the methods given in (4). Each of the reduced pressure test results was compared with the results of the atmospheric tests, and confidence numbers for the ten-percent life were calculated and are given in

Table 2. These confidence numbers indicate the percentage of the time that the ten-percent life obtained with each series of tests at the reduced pressure condition will have the same relation to the ten-percent life of the atmospheric tests. Thus, a confidence number of 60 percent means that 60 out of 100 times the specimens tested at the reduced pressure condition will give results similar to those in Table 2. A 68-percent confidence is approximately equal to a one-sigma deviation. For statistical pruposes, a one-sigma deviation is considered insignificant. Thus, there is no real difference in life at reduced pressure and at atmospheric conditions.

While no statistical significance can be related to the differences in life at reduced pressure and at atmospheric pressure conditions, the immersed reduced-pressure tests had a life approximately 50 percent less than those run under reduced pressure with the quasi-mist lubrication. The calculated confidence number between these two tests is approximately 70 percent at the ten-percent life level. Again no significance can be attributed to this difference in life. Therefore, it can be concluded that while there may be some effects of a reduced pressure environment and lubrication method on fatigue life, these effects are statistically insignificant.

A profile trace of an SAE 52100 ball specimen run under the reduced pressure environment with immersed mineral oil lubrication is shown in Fig. 5. This trace is also representative of the reduced pressure quasi-mist condition and the atmospheric tests with the SAE 52100. The areas of deformation are a relatively large proportion of the total area of deformation plus wear. This indicates minimal wear and thus the presence of elastohydrodynamic lubrication with the mineral oil.

No significant differences existed either with respect to track depth or displaced area, regardless of the pressure environment or lubrication mode employed. This finding correlates with the fatigue results reported herein which did not statistically distinguish any difference in life between the different lubrication modes at reduced pressure and that at atmospheric environment.

It is believed that the reduced pressure environmental conditions of the tests are of such a nature as to be found in many closed cycle space power system applications. It can therefore be concluded from these tests that a reduced pressure environment should have no significant effect on the rolling-element bearing endurance for practical aerospace applications in semisealed systems. This, of course, is contingent upon the lubricant forming an adequate elastohydrodynamic film.

Polyphenyl Ether Tests

Fatigue tests were conducted in the five-ball fatigue tester shown in Fig. 1b under atmospheric pressure conditions with a 5P4E polyphenyl ether lubricant. These tests were run with AISI M-50 ball specimens of Rockwell C hardness C-64 at a contact angle of 30°, a race temperature of 300 F, and a shaft speed of 10 000 rpm. Initial tests at a maximum Hertz stress of 800 000 psi exhibited such excessive wear and deformation that fatigue tests were not possible. The testing stress was thus reduced 700 000 psi.

Seven test balls were run at these reduced stress conditions . Six tests exceeded the 1000 hour runout time without failure; one failed by fatigue at 640 hours. Profile traces of the upper ball running tracks show that the contact stress was approximately 550 000 to 600 000 psi.

In order to determine the effect of a reduced pressure environment on rolling-element fatigue life with a polyphenyl ether, tests were conducted in the five-ball fatigue tester (Fig. 1a) with a 4P3E polyphenyl ether. These tests, designed to approximate conditions in a lubrication system in a space power generation system such as Snap-8, were run with AISI M-50 balls at 300 F race temperature. Wear in the upper ball running tracks in initial tests was so great that it was not feasible to run long term fatigue tests in this tester at reduced pressure. Maximum Hertz stresses as low as 325 000 psi and contact angles as low as 20^{o} were used. The large amount of wear typical of these tests is illustrated in Fig. 6 for only six hours running time. Tests at atmospheric pressure (in argon) at the same conditions show that, with the 4P3E polyphenyl ether, the wear rate at reduced pressure is much greater than the wear rate at atmospheric pressure. A more detailed description of these tests and the results are presented in (3).

Based upon the large amount of wear with both the 5P4E and the 4P3E polyphenyl ethers it is doubtful that an elastohydrodyanmic film could be present with a polyphenyl ether under the stresses and sliding velocities present in the five-ball system which simulates an angular-contact ball bearing. However, an elastohydrodynamic film with a polyphenyl ether under nearly pure rolling conditions is possible at very low stresses (≈ 140 000-psi maximum Hertz stress) and at surface speeds much greater than those in the five ball system (6). Thus, it is concluded that where elastohydrodynamic lubrication is marginal or nonexistent, wear or other surface distress will be the criterion for failure.

GENERAL COMMENTS

Based upon the results reported herein there is no significant effect of operation with a super-refined mineral oil at a reduced pressure environment on fatigue life, fatigue life scatter, material deformation, rolling-element wear, and hence, on elastohydrodynamic lubrication. Therefore, it may be concluded that the load capacity criteria governing the design and operation of bearings at atmospheric pressure may be successfully employed for space applications which utilize a semisealed system where the vapor pressure of the lubricating fluid is the ambient pressure. However, where a rolling-element system is being lubricated under marginal elastohydrodynamic or boundary lubrication conditions such as with the polyphenyl ether, wear of the rolling elements may be much more severe under a reduced pressure environment. For this case, the factor limiting system operation will be wear and not fatigue.

SUMMARY

A modified NASA five-ball fatigue tester was used to investigate the effect of a reduced pressure environment on rolling-element fatigue life. Tests were run with SAE 52100 ball specimens at a contact angle of 20^{o}, a maximum Hertz stress of 800 000 psi, and a speed of 4900 RPM with no heat added, with a super-refined naphthenic mineral oil as the lubricant in an atmospheric pressure environment. At the conclusion of the atmospheric pressure tests two series of tests were run under the same conditions with the exception that the ambient pressure was approximately that of the vapor pressure of the lubricant. The first series of reduced pressure tests was conducted with the lubricant introduced into the test chamber in a quasi-mist form. In the second series of reduced pressure tests the ball specimens were immersed in the lubricating fluid. Fatigue tests were conducted with AISI M-50 ball specimens at atmospheric environmental conditions, a 30^{o}

contact angle, a maximum Hertz stress of 700 000 psi, a spoed of 10 000 rpm, and a temperature of 300 F with a 5P4E polyphenyl ether as the lubricant. Rolling-element studies were also conducted with a 4P3E polyphenyl ether lubricant at atmospheric and reduced pressure conditions. The following results were obtained:

1. Differences in fatigue life, plastic deformation and wear with the mineral oil lubricant between tests conducted at atmospheric pressure levels and those at reduced pressure were insignificant regardless of the lubrication method employed.

2. For the mineral oil lubricant, minimal wear occurred under both the atmospheric and reduced pressure environments indicating the presence of elastohydrodynamic lubrication. However, for the polyphenyl ether lubricants extensive wear occurred at atmospheric pressure conditions suggesting the lack of an elastohydrodynamic lubricant film at high contact stresses.

3. Where elastohydrodynamic lubrication conditions exist, the design criteria employed for bearings used for atmospheric operation may successfully be employed for bearings used in a semisealed system where the ambient pressure is that of the vapor pressure of the lubricating fluid.

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TABLE I. - PHYSICAL PROPERTIES OF TEST LUBRICANTS

(MANUFACTURER'S DATA)

Property	Super-refined naphthenic mineral oil	5P4E poly-phenyl ether	4P3E poly-phenyl ether
Density, g/ml			
0 F	0.908	-------	-------
100 F	.873	1.187	1.17
200 F	.838	1.143	1.12
300 F	.802	1.100	-------
400 F	.768	1.057	1.04
500 F	.732	1.013	-------
Vapor pressure, mm Hg (extrapolated)			
125 F	$<10^{-5}$	-------	-------
300 F	.07	-------	-------
400 F	2.0	-------	-------
500 F	17.0	.7	3.2
600 F	----------	5.3	24.0
700 F	----------	26	140.0
Viscosity, centistokes			
0 F	10 000	-------	-------
30 F	1 500	-------	-------
100 F	79	363	69.6
210 F	8.4	13.1	6.3
500 F	1.1	1.2	-------
700 F	.6	.65	.5
Cleveland open cup flash point, ^{o}F	445	550	500
Cleveland open cup fire point, ^{o}F	495	660	565
ASTM pour point, ^{o}F	-30	40	19

TABLE 2. - RESULTS OF FATIGUE TESTS IN FIVE-BALL FATIGUE TESTER

(Maximum Hertz stress, 800 000 psi, lubricant, super-refined naphthenic mineral oil; contact angle, 20°; ball material, SAE 52100; shaft speed, 4900 rpm; race temperature, 130 F.)

Environment	Lubrication mode	Ten-percent fatigue life, millions of stress cycles	Fifty-per-cent fatigue life, millions of stress cycles	Weibull slope	Confidence number at ten-percent life level	Failure index
Atmospheric pressure	Drop feed	23	122	1.1	---	25 failures of 38 tested
Reduced pressure[a]	Quasi-mist[b]	34	168	1.2	60%	13 failures of 22 tested
Reduced pressure	Immersed	18	98	1.1	58%	10 failures of 10 tested

[a]Lubricant vapor pressure, approximately 2×10^{-6} Torr at 120 F.

[b]Lubricant was drop feed, upon entrance to the test chamber, the lubricant became a quasi-mist due to the reduced pressure.

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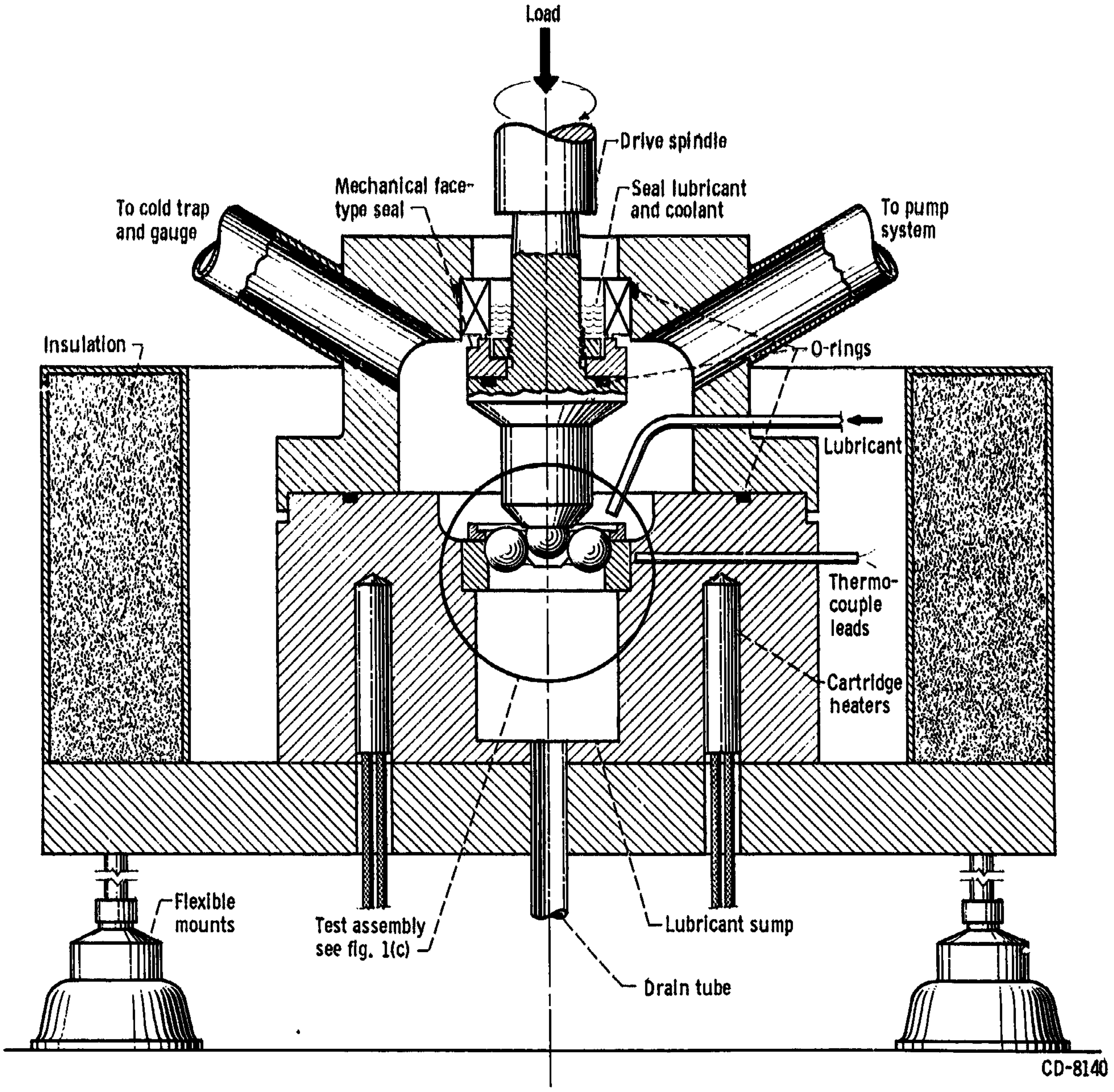

(a) Section view showing modifications for lubrication tests at reduced pressures.

Figure 1. - Five-ball fatigue tester.

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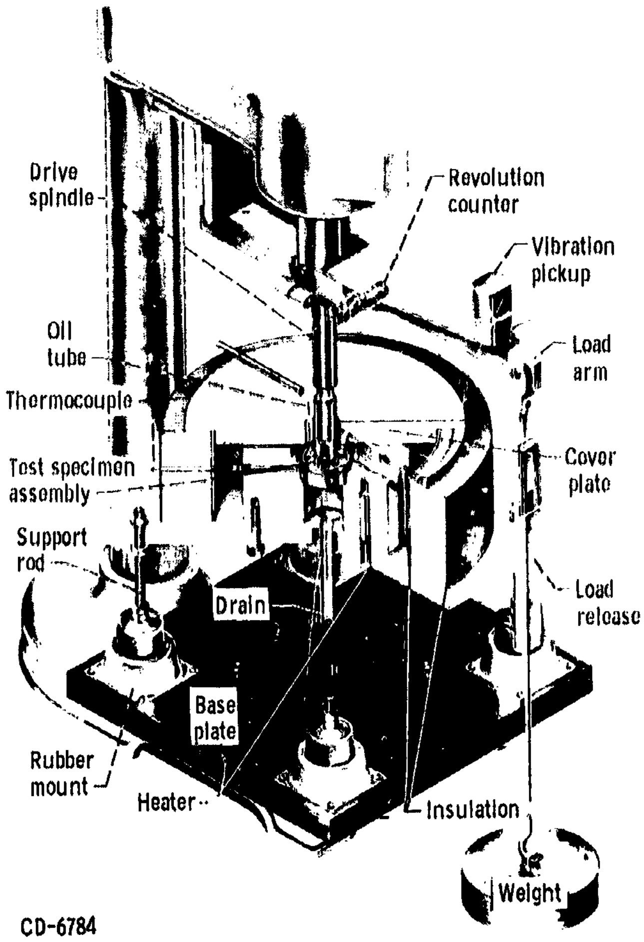

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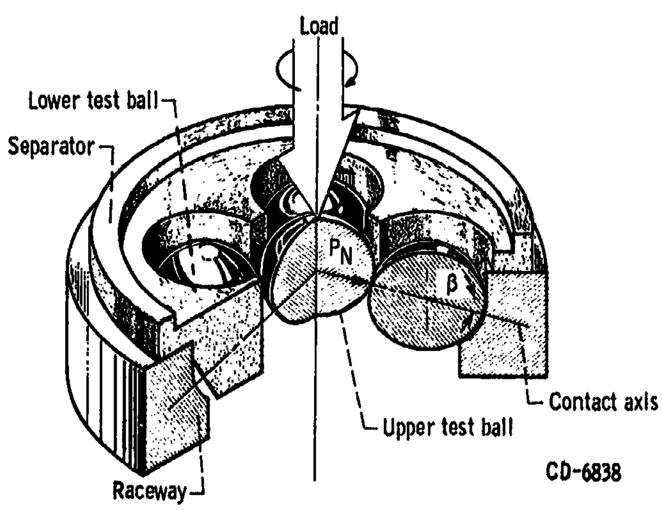
(b) View of tester before modification.



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(c) Test assembly.
Figure 1. - Concluded.

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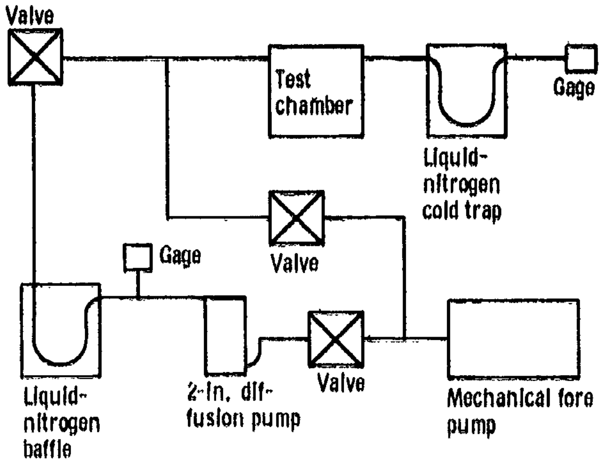
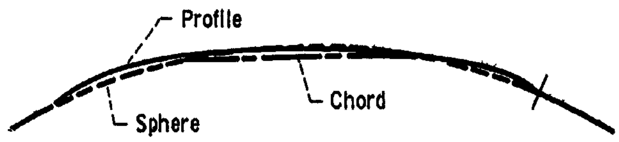
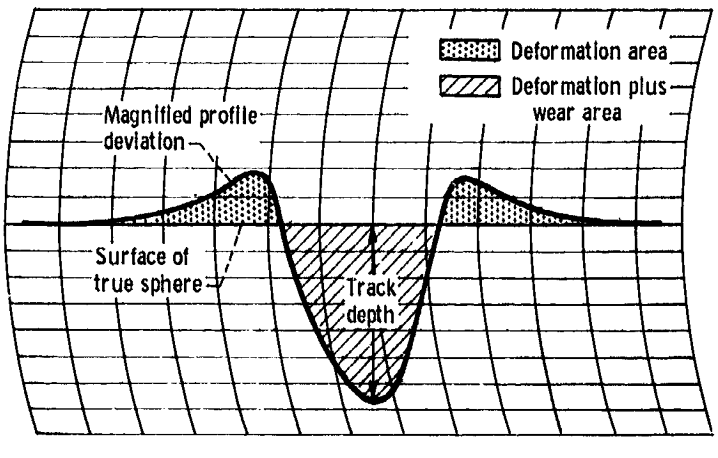


Figure 2. - Schematic diagram of vacuum system.



(a) Schematic diagram of transverse section of ball surface.



(b) Transverse profile trace of ball running track at high magnification.

Figure 3. - Transverse section of ball running track.

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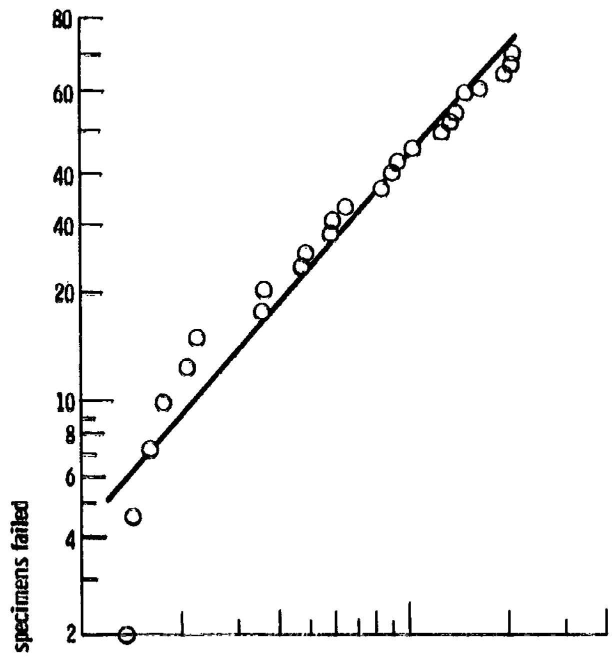
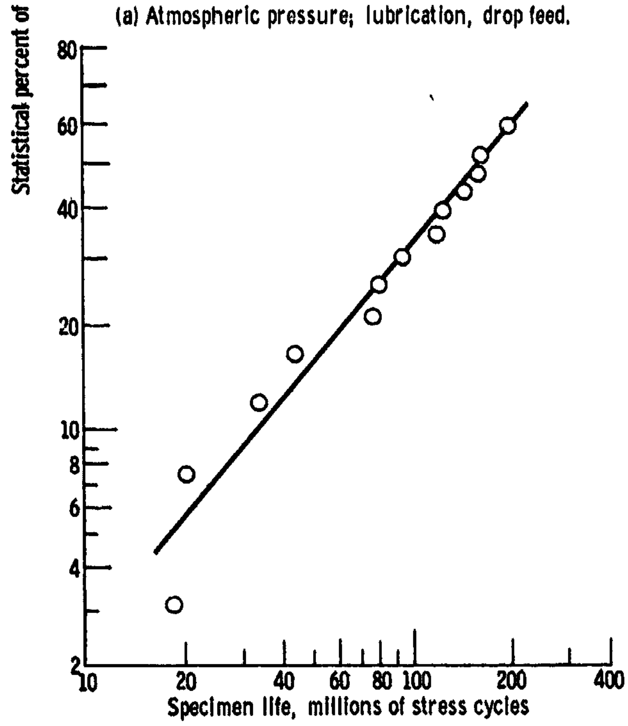
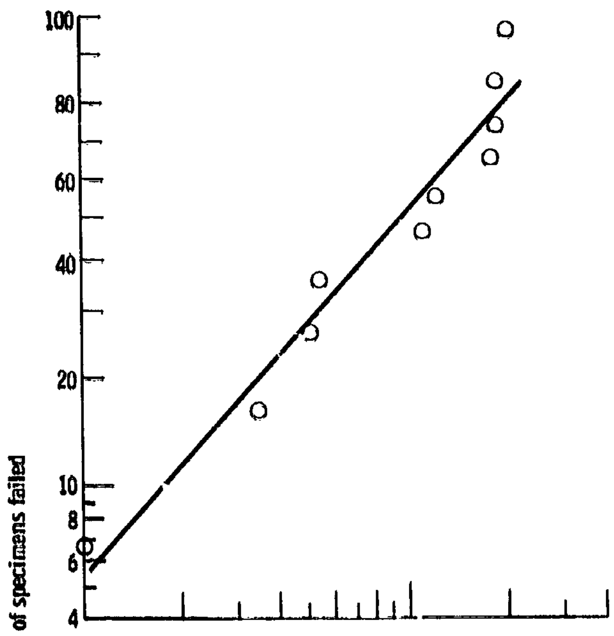


(a) Atmospheric pressure; lubrication, drop feed.

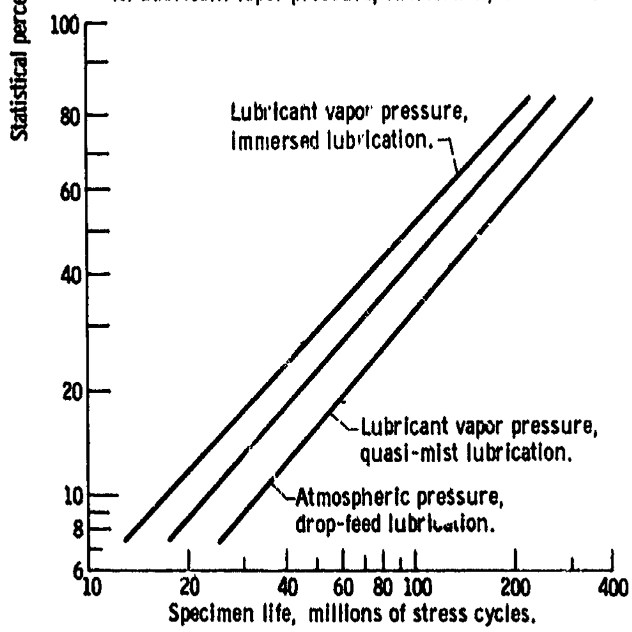


(b) Lubricant vapor pressure; lubrication, quasi-mist.

Figure 4. - Rolling-element fatigue life at atmospheric and reduced pressures in five-ball fatigue tester. Shaft speed, 4900 rpm; contact angle, 20°; race temperature, 130 F; maximum Hertz stress, 800 000 psi; lubricant, super-refined naphthenic mineral oil.



(c) Lubricant vapor pressure; lubrication, immersed.



(d) Summary.

Figure 4. - Concluded.

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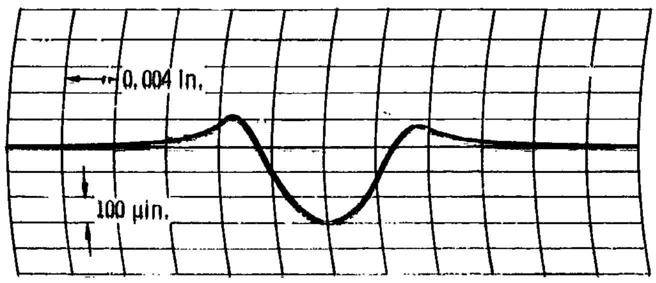
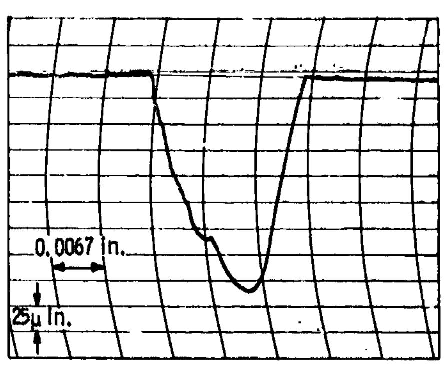


SAE 52100 ball run with super-refined naphthenic mineral oil at reduced pressure. Maximum Hertz stress, 800 000-psi; race temperature, 130 F; shaft speed, 4900 rpm; contact angle, 20°; duration, 150 hours.

Figure 5. - Transverse profile trace of representative ball specimens.



As-received 4P3E polyphenyl ether.

Figure 6. - Typical profile of upper ball running track with 4P3E polyphenyl either at reduced pressure. Maximum Hertz stress, 575 000 psi; race temperature, 300 F; shaft speed, 4900 rpm; contact angle, 20°; duration, 6 hours.