NASA TECHNICAL NOTE

NASA TN D-8124

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ROLLING-ELEMENT FATIGUE LIFE WITH TWO SYNTHETIC CYCLOALIPHATIC TRACTION FLUIDS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1976

1. Report No. NASA TN D-8124	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ROLLING-ELEMENT FATIGUE LIFE WITH TWO SYNTHETIC CYCLOALIPHATIC TRACTION FLUIDS		5. Report Date March 1976
		6. Performing Organization Code
7. Author(s) Stuart H. Loewenthal and Richard J. Parker		8. Performing Organization Report No. E-8457
		10. Work Unit No. 505-04
9. Performing Organization Name and Address NASA Lewis Research Center and U. S. Army Air Mobility R&D Laboratory 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

The life potential of two synthetic cycloaliphatic hydrocarbon traction fluids in rolling-element fatigue was evaluated in a five-ball fatigue tester. Life comparisons with a MIL-L-23699 qualified tetraester oil showed that the traction test oils had good fatigue life performance, comparable to that of the tetraester oil. No statistically significant life differences between the traction fluids and the tetraester oil were exhibited under the accelerated fatigue test conditions. Erratic operating behavior was occasionally encountered during tests with the anti-wear additive containing traction fluid for reasons thought to be related to excessive chemical activity under high contact pressure. This behavior occasionally resulted in premature test termination due to excessive surface distress and overheating.

17. Key Words (Suggested by Author(s)) Zinc dithiophosphate; Lubricant additives; Bearing fatigue life; Bearings; Lubrication; Traction; Traction lubricants		18. Distribution Statement Unclassified - unlimited STAR Category 37	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 16	22. Price* $3.25

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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SUMMARY

Rolling-element fatigue tests were conducted in a five-ball fatigue tester using two synthetic cycloaliphatic hydrocarbon traction fluids and a MIL-L-23699 qualified tetraester oil. These oils were tested using AISI 52100, 12.7-millimeter (0.500-in.) diameter steel balls under a maximum Hertz stress of 5.52×10^{9} pascals (800 000 psi) at a shaft speed of 10 700 rpm. Race temperatures, with no heat added, were nominally 8 K (15° F) higher for the traction fluids than for the tetraester oil due to increased lubricant spin heating.

The rolling-element fatigue lives obtained with the cycloaliphatic traction fluids were not significantly different on a statistical basis from those obtained with the tetraester oil.

Erratic test behavior was observed in those tests using the traction fluid that contained an antiwear additive. Rolling-element surface distress and overheating occasionally caused premature termination of tests with this lubricant.

INTRODUCTION

Recently there has been renewed interest in mechanical transmissions which use the principle of traction for power transfer. In these devices torque is transmitted between rolling elements across a thin lubricant film under high contact pressure. Consequently, the magnitude of the contact pressure required to transmit a given amount of torque is principally dependent on the tractive properties of the lubricant. Lubricants formulated for traction drive applications typically have high coefficients of traction. These oils are generically referred to as traction fluids.

Although the virtues of traction drives have been known for sometime (viz., smooth, quiet power transfer, infinitely variable ratio operation, and high mechanical efficiency), the power capacity of United States commercial drives to date has been quite limited, rarely exceeding 20 horsepower (refs. 1 and 2). The primary difficulty of developing reasonably sized traction drives for medium- to high-power applications has been one of roller component durability. The contact pressure needed to transmit significant power through these devices is quite high, often above maximum Hertz stresses of 2.42×10^{9} pascal (350 000 psi). Because the drive's design life, similar to the fatigue life of rolling-element bearings, is commonly taken to be inversely related to contact pressure raised to the 9th power, high powered traction drives have normally been restricted to limited-life applications. However, with the advent of cleaner bearing steels, which provide greater fatigue life performance (ref. 3), and the development of lubricants with better tractive properties (refs. 4 and 5), traction drives can transmit more power for a given size package and still provide adequate service life.

Apart from potential drive life improvements stemming from reduced contact loading as a result of the lubricant's higher traction coefficient, some investigators (ref. 6) suggest that traction fluids may show fatigue life performances that are superior to conventional lubricants on a direct basis. This is attributed, in part, to the traction fluid's relatively high pressure-viscosity coefficient α at temperatures to about 372 K (210° F) (ref. 7), which makes these lubricants better elastohydrodynamic (EHD) film formers then conventional lubricants of equal viscosity. Increased EHD film thickness has a strong beneficial effect on fatigue life (ref. 3). Thus, an improvement in fatigue life might reasonably be expected for some traction fluids.

In reference 8 full-scale tapered-roller bearing tests with a synthetic cycloaliphatic hydrocarbon traction fluid did show an appreciable life improvement, compared with tests with a petroleum oil of equivalent viscosity. The potential of improved lubricant performance of cycloaliphatic traction fluids in rolling-element fatigue became a major incentive for the present investigation.

The objective of the work reported herein was to evaluate the fatigue life performance of two cycloaliphatic traction fluids in comparison with a tetraester lubricant. Tests were conducted in the NASA five-ball fatigue tester at a maximum Hertz stress of 5.52×10^{9} pascals (800 000 psi), a contact angle of 30°, and a shaft speed of 10 700 rpm.

TEST LUBRICANTS AND MATERIALS

The test lubricants compared in this study consisted of two traction fluids blended from the same base oil and a tetraester (type II) oil. Properties of these lubricants are given in table I.

The high-traction fluids examined were synthetic lubricants from the cycloaliphatic hydrocarbon family. This type of lubricant possesses a relatively high coefficient of traction that is approximately 50 percent greater than conventional mineral oils (ref. 6).

Unlike earlier oils used in traction applications, the new traction oils have sufficient viscosity to promote good EHD film formation and thereby lessen the susceptibility to component wear and fatigue.

The two traction lubricants evaluated contained different additives and had different viscosity characteristics (see fig. 1), due to the presence of a viscosity index (VI) improver, although both were formulated from the same base stock. The lower viscosity sample, referred to herein as traction fluid 1, contained only an oxidation inhibitor. The other sample, traction fluid 2, contained an oxidation inhibitor, a viscosity index improver (polymethacrylate), and antifoam and antiwear additives. The antiwear additive, zinc dialkyl dithiophosphate, is quite common to many automotive oils and transmission fluids.

The tetraester oil contained additives that included oxidation and corrosion inhibitors as well as an antiwear additive. The tetraester oil's kinematic viscosity characteristics, which were similar to the two traction fluids (see fig. 1), made it a good reference test lubricant. In addition, this oil has shown good operating characteristics in high-temperature bearing tests (refs. 9 and 10) and has qualified for use in jet-engine lubrication systems under MIL-L-23699 specifications.

The 12.7-millimeter (0.500-in.) diameter test balls used in this study were made from a single heat of carbon-vacuum-deoxidized (CVD) AISI 52100 steel. The balls were through-hardened to Rockwell C 61.

APPARATUS AND PROCEDURE

Five-Ball Fatigue Tester

The NASA five-ball fatigue tester was used for all tests conducted. The fatigue tester, fully described in reference 11, is shown in figure 2. It consists essentially of an upper test ball pyramided on four lower support balls that are positioned by a separator and are free to rotate in an angular-contact raceway. System loading and drive are supplied through a vertical drive shaft. For every revolution of the drive shaft the upper test ball receives three stress cycles. The upper test ball and raceway are analogous in operation to the inner and outer races of a bearing, respectively. The separator and the lower balls function in a manner similar to the race and the balls in a bearing.

Fatigue Testing

Before they were assembled in the five-ball fatigue tester, all test-section components were flushed and scrubbed with ethyl alcohol and wiped dry with cheesecloth. The specimens were examined for imperfections at a magnification of ×15. After examination all specimens were coated with the test lubricant to prevent corrosion and wear at startup. A new set of lower balls was used with each upper test-ball specimen. The speed, outer-race temperature, and oil flow were monitored and recorded at regular intervals. After each test the outer race of the five-ball system was examined visually for damage. If any damage was observed, the race would be replaced before further testing.

Method of Presenting Fatigue Results

The total test time for each specimen was recorded and converted to total stress cycles. The statistical methods of reference 12 for analyzing rolling-element fatigue data were used to obtain a plot of the log log of the reciprocal of the probability of survival as a function of the log of stress cycles to failure (Weibull coordinates). For convenience, the ordinate is graduated in statistical percent of specimens failed. From these plots, the number of stress cycles necessary to fail any given portion of the specimen group may be determined. Where high reliability is of paramount importance, the main interest is in early failures. For comparison, the 10-percent life on the Weibull plot was used. The 10-percent life is the number of stress cycles within which 10 percent of the specimens can be expected to fail; this 10-percent life is equivalent to a 90-percent probability of survival. The failure index indicates the number of specimens that failed out of those tested.

RESULTS AND DISCUSSION

Fatigue Results

Rolling-element fatigue tests were run in the five-ball fatigue tester with two traction fluids and a tetraester oil, which was included for comparison. The 12.7-millimeter (0.500-in.) diameter balls tested were made from a single melt of carbon vacuum deoxidized AISI 52100 steel. Standard test conditions for all tests consisted of room temperature (i.e., no heat added), a maximum Hertz stress of 5.52×10^{9} pascals (800 000 psi) at a contact angle of 30°, and an upper ball speed of 10 700 rpm. Outer-race temperatures for the tetraester lubricant tests average approximately 339 K (150° F). Race temperatures averaged approximately 347 K (165° F) for both grades of traction fluid. Higher race operating temperatures were recorded in tests with both traction fluids, despite the fact that these oils actually had a lower kinematic viscosity than did tetraester oil at test conditions. The observed higher temperatures can be attributed to increased spinning friction in the contact zone as a result of the traction fluids' relative high traction coefficient. Because of the adverse effect of the higher temperature on elastohydrodynamic (EHD) film formation, contact spin heating can be of major concern for traction drive designers who specify traction oils.

The results of the rolling-element fatigue tests are shown on Weibull coordinates in figure 3 and are summarized in table II. In general, the 10-percent fatigue lives obtained with the traction fluids are at least as good as that obtained with the tetraester oil. The statistical significance of this comparison is reflected by the confidence numbers in table II, which were calculated by the methods of reference 12. The value of these confidence numbers indicates the percentage of time that components lubricated with the traction fluids would show fatigue lives superior to the fatigue lives of the same components lubricated with the tetraester oil. A confidence number greater than 95 percent, which is equivalent to a 2 σ confidence level, indicates a high degree of certainty. The small apparent life advantages observed for the traction fluids are not considered statistically significant except for traction fluid 1 at the 50-percent life level.

Although good correlation has been repeatedly demonstrated between the relative fatigue life performance of lubricants tested in the five-ball apparatus and that actually experienced in full-scale bearing tests (e.g., see ref. 13), it is conceivable that unforeseen chemical-stress effects may alter the aforementioned life rankings of the test lubricants at the lower contact stress levels associated with typical bearing and traction drive applications. Undoubtedly the safest course to follow, particularly for critical applications, would be to conduct fatigue life tests for unconfirmed lubricants at the contact stress level of interest. This of course is not always a practical option.

All fatigue failures considered in the present analysis appeared to be a result of classical subsurface fatigue; that is, each of the failed balls had a single fatigue spall located in the running track. These spalls (one of which is shown in fig. 4(a)) are similar to those obtained in previous five-ball fatigue experiments (ref. 14).

Lubricant Viscosity Effects

The operating temperature was not a controlled variable in these five-ball fatigue tests. The room temperature and the lubricant mist temperature were controlled, and the test system was allowed to seek a stabilized temperature. As mentioned previously, the tests with the traction fluids stabilized at a race temperature approximately 8 K (15° F) higher than that for the tetraester fluid. Consequently, the operating viscosities of the traction fluids were somewhat less than that of the tetraester at the test conditions.

Lubricant viscosity is known to influence rolling-element fatigue life. References

15 and 16 report that rolling-element fatigue life is proportional to the kinematic viscosity raised to powers from 0.2 to 0.3. The viscosity of the lubricant as it enters the contact is the proper parameter to use in this relation. Unfortunately, it was impractical to measure the temperature of the lubricant at this point. Considering the relative viscosities of the test lubricants at the measured race temperatures and their effect on fatigue life in accordance with the aforementioned relation, however, life adjustment factors can be estimated for tests that might have been run at equal lubricant viscosities. These tests would, of course, require additional lubricant cooling for the hotter running traction fluids. Correcting for the lubricant viscosity advantage of the tetraester oil would result in a fatigue life improvement for traction fluids 1 and 2 of 18 and 7 percent, respectively. These small adjustments should not have a significant effect on the relative fatigue life comparison of the lubricants tested.

Test Behavior of Traction Fluid

In the case of traction fluid 2, some difficulties were encountered in establishing and maintaining test operating conditions. Several tests had to be discontinued within minutes of initiation because of severe wear and overheating. A pronounced wear track is quite evident on the upper ball specimen of figure 4(b), which was removed from the tester after just 30 minutes of operation. Test balls from these aborted tests generally showed a high degree of discoloration from overheating. Those tests that failed to achieve stable operation within 1 hour were terminated, treated as voids, and eliminated from statistical consideration. Eight tests fit this category.

In ten cases, test specimens lubricated with traction fluid 2 did achieve and maintain stable running conditions, but after several hours of testing, unexpectedly began to run roughly and overheat. Figure 4(c) shows an upper ball that ran smoothly for more than 50 hours before it began to overheat and wear drastically. The appearance of this ball with its excessive surface distress when contrasted against that of a ball operated under identical conditions which reached the 100-hour cut-off time (fig. 4(d)) exemplifies the erratic behavior of traction fluid 2.

Examination of the test rig's oil jets before and after failures showed them to be in good working order. It is considered unlikely that temporary lubricant deprivation is the proper explanation. Tests that were halted for excessive surface distress, that is, nonfatigue failures, were treated as suspensions in the statistical analysis.

The behavior of traction fluid 2 is even more perplexing in view of the fact that surface distress was not encountered in any of the tests with traction fluid 1. Traction fluid 1 not only appeared to be less viscous but did not have the benefit of an antiwear additive as did fluid 2.

Additive Effects

As noted previously, a polymeric additive known as methacrylate was added to the base stock oil of traction fluid 1 to obtain traction fluid 2, which had better viscosity-temperature characteristics. It is common in the petroleum industry to use a high molecular weight additive, referred to as a viscosity index improver, to obtain several viscosity grades of oil from the same base stock. However, the degree of viscosity enhancement actually achieved by the addition of such a long chain polymer is often dependent on the operational shear rate to which the oil blend is subjected. Published test data for polymethacrylate has shown that it ceases to behave in a Newtonian manner at even modest shear rates of 100 reciprocal seconds or higher (ref. 17). In fact, in a journal bearing tester at shear rates above 5×10^4 reciprocal seconds, polymethacrylate's viscosity contribution to the blend was nearly totally lost; that is, the viscosity of the base oil with the polymeric additive approaches that of the base oil alone (ref. 17). Thus, at the high shear rates that exist in the five-ball fatigue tester (greater than 10^6 sec^{-1}), it is likely that the actual viscosities of both traction fluids were nearly the same. In view of this, it is not surprising that both traction fluids had approximately the same 10-percent fatigue lives even though fluid 2 enjoyed about a 60 percent apparent viscosity advantage over fluid 1. Unfortunately, this loss in operating viscosity does not help to explain the erratic wear behavior encountered with just one of the traction test oils.

Another distinction between fluids 1 and 2 is the presence of an antiwear additive. The role played by surface reactive antiwear additives under the relatively high loading conditions that exist in the five-ball fatigue tester is not well defined. Under conventional loading conditions for bearings and gears, that is, maximum Hertz stresses typically less than 2.07×10^9 pascals (300 000 psi), antiwear additives form chemical surface films, which presumably minimize asperity contact and, subsequently, surface distress. At relatively high pressures chemical effects become a significant factor and could conceivably have an adverse effect on rolling-element life. Tests reported in reference 18, performed in a four-ball fatigue tester under an unusually high maximum Hertz stress loading of 8.3×10^9 pascals (1.2×10^6 psi), showed an increase in specimen surface distress with the addition of an antiwear additive in about half of the material-additive tests conducted. Similarly, tests conducted with the NASA five-ball fatigue rig (ref. 19) showed that the presence of several surface active additives were generally detrimental to rolling-element fatigue life, although only a chlorinated wax additive caused test ball surface distress.

Neither of the aforementioned studies (refs. 18 and 19) used the zinc dialkyl dithiophosphate antiwear additive that is present in traction fluid 2. Despite its wide use, the manner in which zinc dithiophosphate provides antiwear protection is still unclear (ref. 20). The research of reference 21, conducted with the four-ball apparatus mentioned previously, did examine the effects of the dialkyl phosphate additive but, unfortunately, failed to differentiate fatigue related failures and those caused by gross surface distress or smearing. The results of reference 21 indicate that rolling-element life can be improved with the zinc dialkyl dithiophosphate mixed with a naphthenic mineral oil, with an oxidation inhibitor (test oil A), for additive concentration less than 3 percent by weight. At higher additive concentrations or for test oil A without an oxidation inhibitor, test life was markedly reduced. The presence of the dialkyl phosphate additive in test oil B, another naphthenic mineral oil which contained no oxidation inhibitors, caused significant life reductions at all concentration levels.

Although the aforementioned data are far from conclusive, they do suggest that overreactive chemical effects of the antiwear additive under high contact pressure might be responsible for the erratic behavior observed in the tests with traction fluid 2.

This hypothesis is strengthened by the study reported in reference 21 in which the load-carrying performance of a range of metal dialkyl dithiophosphates were studied in a four-ball wear apparatus under both antiwear and extreme pressure conditions. The major distinction between antiwear and extreme pressure regions of lubrication is in terms of the severity of the load and the attendant contact operating temperatures. A significant conclusion of reference 22 is "that good performance by an additive in the antiwear region is not necessarily accompanied by good performance in the extreme pressure region." In fact, the zinc dithiophosphate additive, which exhibited the best antiwear performance of all the metal dithiophosphates tested in reference 22, provided the poorest protection under extreme pressure conditions.

SUMMARY OF RESULTS

Rolling-element fatigue tests were conducted in a five-ball fatigue tester using two synthetic cycloaliphatic hydrocarbon traction fluids and a tetraester oil qualified under MIL-L-23699 specifications. Test conditions for all tests include a maximum Hertz stress of 5.52×10^{9} pascals (800 000 psi), a shaft speed of 10 700 rpm, a contact angle of 30°, and nominal race temperatures (with no heat added) of 339 K (150° F) and 347 K (165° F) for the tetraester and traction oils, respectively. AISI 52100, 12.7-millimeter (0.500-in.) diameter steel balls were used as test specimens. The following results were obtained:

1. Rolling-element fatigue lives obtained with the traction test fluids were not significantly different from that obtained with the tetraester oil.

2. Erratic test behavior was observed for the traction fluid that contained a zinc dialkyl dithiophosphate antiwear additive. Some tests were terminated prematurely because of excessive surface distress and overheating. No definitive explanation can be

offered for these occurrences although overreactive surface chemistry might be partially responsible.

3. Slightly higher outer-race temperatures were recorded for the traction fluids than for the tetraester oil. This difference is believed to be due to lubricant spin heating within the contact zone as a result of the traction fluids' relatively high coefficients of traction.

Lewis Research Center,
National Aeronautics and Space Administration,
and
U. S. Army Air Mobility R&D Laboratory,
Cleveland, Ohio, December 8, 1975,
505-04.

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TABLE I. - TEST LUBRICANT PROPERTIES

Property	Lubricant description		
	Tetraester	Traction fluid	
		1	2
Additives	Antiwear Oxidation inhibitor ---------------- ----------------	Oxidation inhibitor ---------------- ---------------- ----------------	Antiwear[a] Oxidation inhibitor Antifoam Viscosity index improver[b]
Kinematic viscosity, cm^2/sec, at -			
244 K (-20° F)	3000×10^{-2}	$31\ 600\times10^{-2}$	$41\ 500\times10^{-2}$
311 K (100° F)	29×10^{-2}	23×10^{-2}	34×10^{-2}
372 K (210° F)	5.3×10^{-2}	3.7×10^{-2}	5.6×10^{-2}
477 K (400° F)	1.3×10^{-2}	--------	--------
Flash point, K; °F	533; 500	422; 300	435; 325
Fire point, K; °F	Unknown	435; 325	447; 345
Autoignition temperature, K; °F	694; 800	589; 600	600; 620
Pour point, K; °F	214; -75	230; -45	236; -35
Specific heat at 311 K (100° F), J/kg·K; Btu/(lb)(°F)	1920; 0.467	2130; 0.51	2130; 0.51
Thermal conductivity at 311 K (100° F), J/m·sec·K; Btu/(hr)(ft)(°F)	0.16; 0.094	0.10; 0.060	0.10; 0.060
Specific gravity at 311 K (100° F)	0.977	0.886	0.889

[a]Zinc dialkyl dithiophosphate.
[b]Polymethacrylate.

TABLE II. - ROLLING-ELEMENT FATIGUE LIFE OF AISI 52100 STEEL BALLS LUBRICATED WITH SYNTHETIC CYCLOALIPHATIC TRACTION FLUIDS OR TETRAESTER OIL IN FIVE-BALL FATIGUE TESTER

[Maximum Hertz stress, 5.52×10^9 Pa (800 000 psi); shaft speed, 10 700 rpm; contact angle, 30°.]

Lubricant	Rolling-element fatigue life, millions of upper-ball stress cycles		Weibull slope	Failure index[a]	Confidence number[b], percent	
	10-Percent life, L_{10}	50-Percent life, L_{50}			10-Percent life, L_{10}	50-Percent life, L_{50}
Tetraester oil[c]	14.3	71.1	1.17	35 out of 39	--	--
Synthetic cycloaliphatic traction fluid[d]:						
1	17.9	115.9	1.01	21 out of 32	60	97
2	17.3	72.7	1.31	15 out of 28	58	51

[a]Number of failures out of total number of tests.

[b]Percentage of time that fatigue life with traction fluids will be greater than (or less than, as the case may be) life with tetraester oil.

[c]Race temperature, 339 K (150° F).

[d]Race temperature, 347 K (165° F).

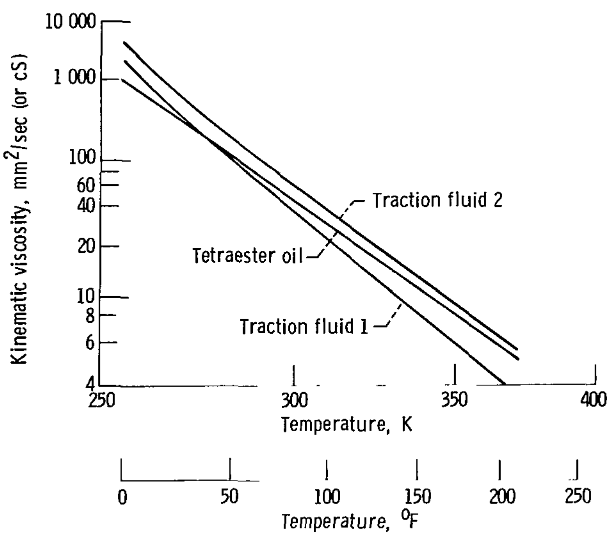
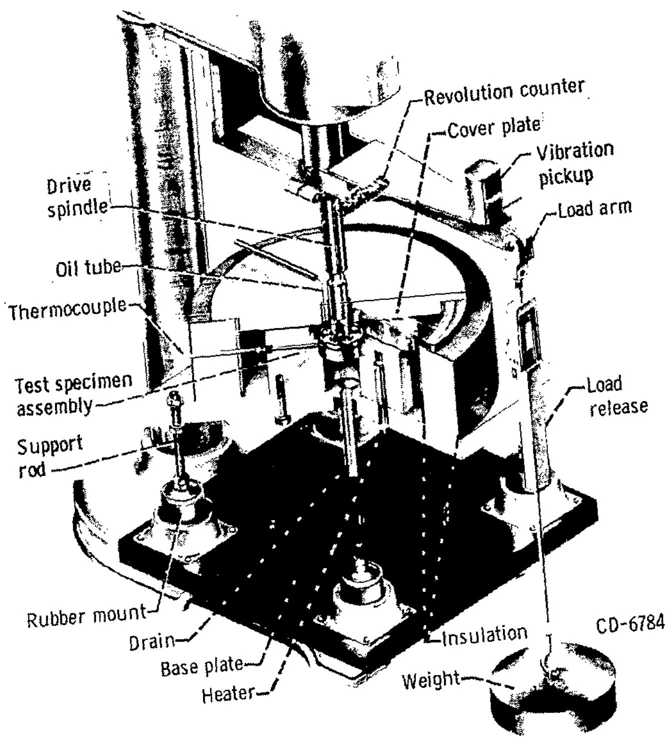
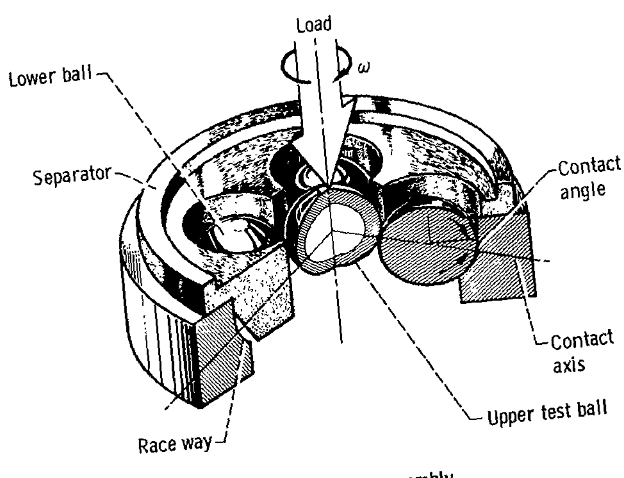


Figure 1. - ASTM chart of test lubricants' kinematic viscosity as function of temperature.

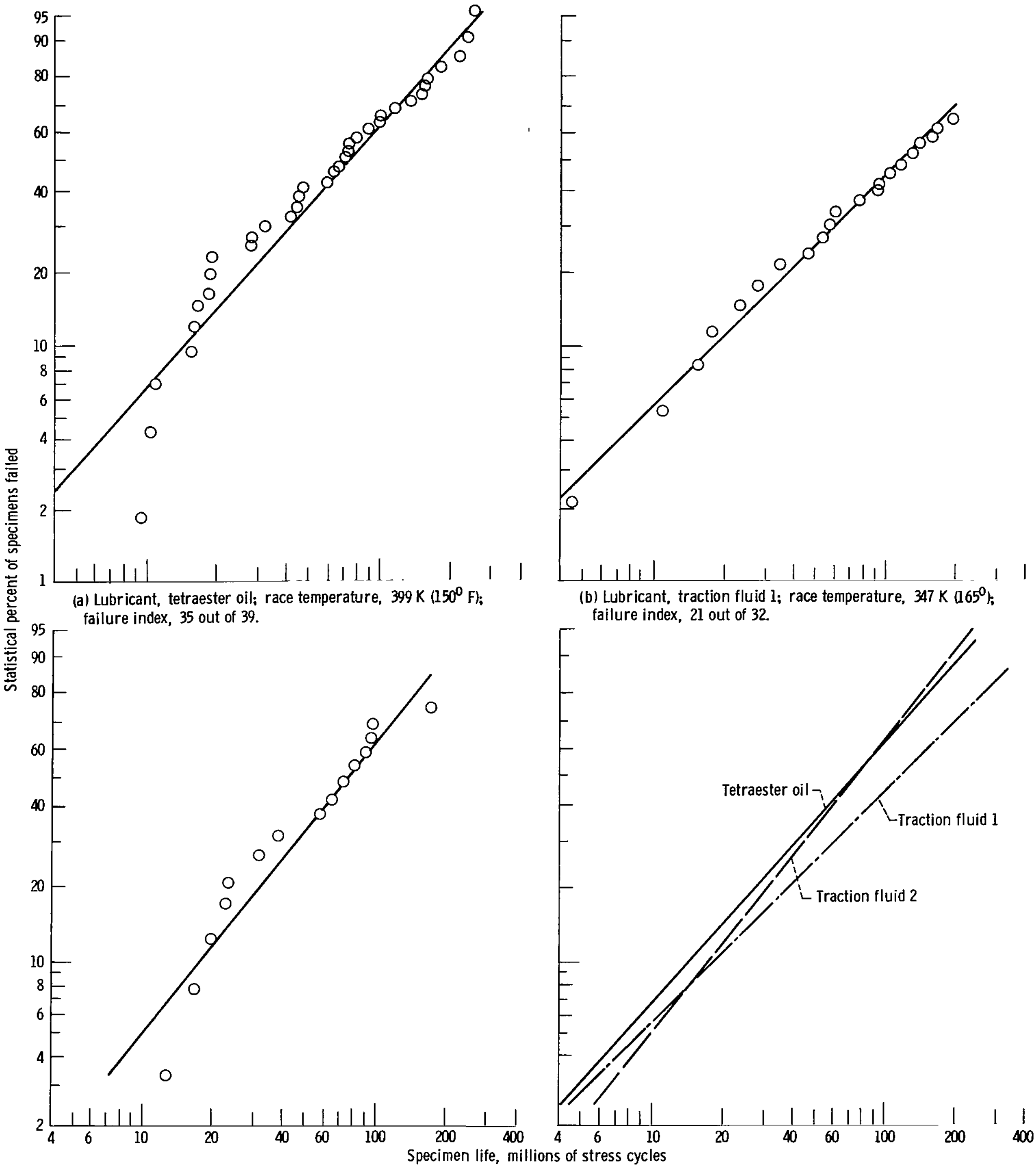


(a) Cutaway view of five-ball fatigue tester.



(b) Five-ball test assembly.

Figure 2. - Test apparatus.



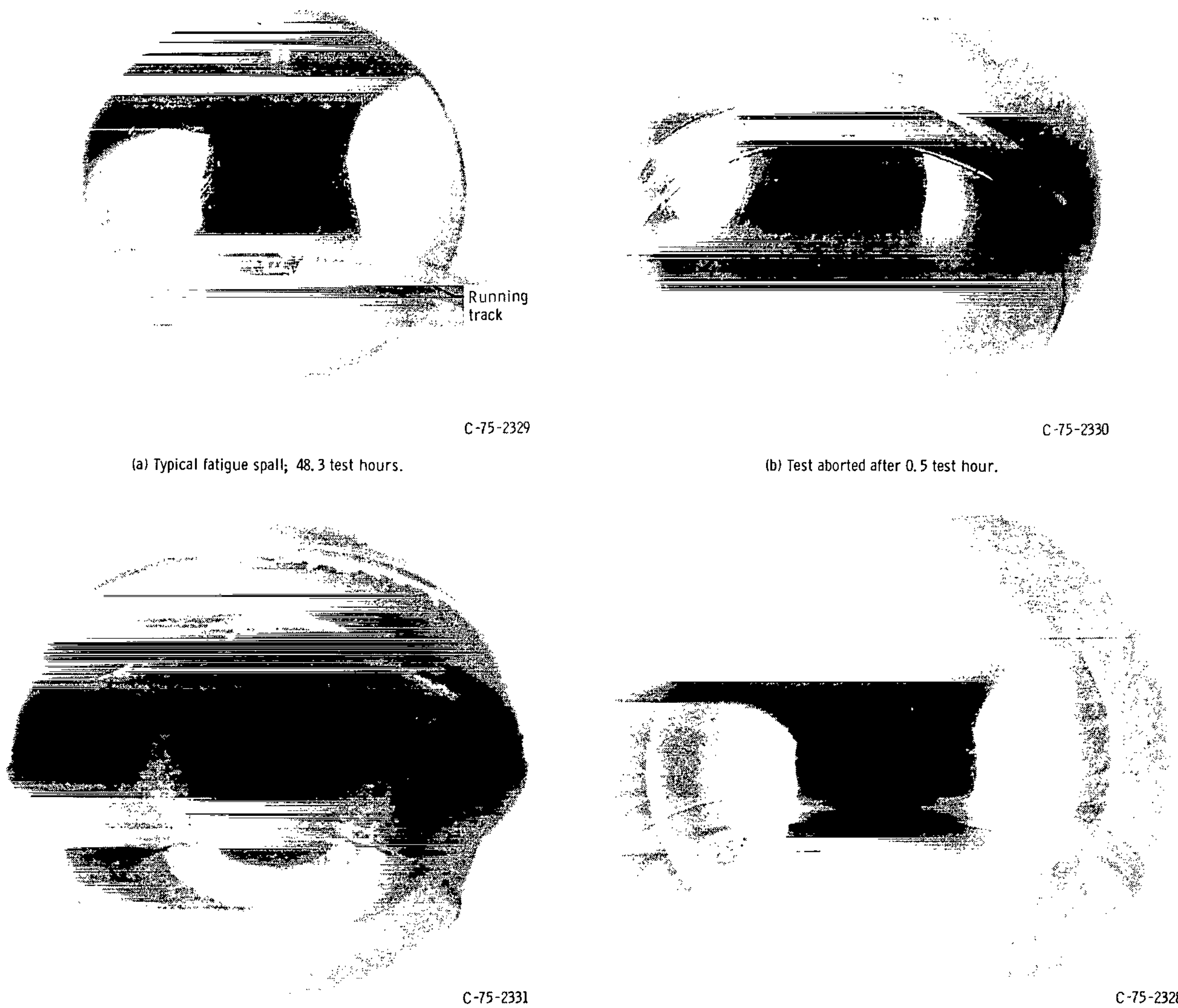
(a) Lubricant, tetraester oil; race temperature, 399 K (150° F); failure index, 35 out of 39.

(b) Lubricant, traction fluid 1; race temperature, 347 K (165°); failure index, 21 out of 32.

(c) Lubricant, traction fluid 2; race temperature, 347 K (165° F); failure index, 15 out of 28.

(d) Summary.

Figure 3. - Rolling-element fatigue life of lubricated AISI 52100 balls in a five-ball fatigue tester. Maximum Hertz stress, 5.52×10^9 pascals (800 000 psi); shaft speed, 10 700 rpm; contact angle, 30°.



(a) Typical fatigue spall; 48.3 test hours.

(b) Test aborted after 0.5 test hour.

(c) Test suspended after 52.6 test hours.

(d) Test runout to 101.3 hours.

Figure 4. - Appearance of upper balls from five-ball fatigue tester lubricated with traction fluid 2.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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