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ADVANCED AIRBREATHING ENGINE LUBRICANTS STUDY WITH A TETRAESTER FLUID AND A SYNTHETIC PARAFFINIC OIL AT 492 K (425° F)

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16. Abstract

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SUMMARY

Groups of 120-millimeter-bore angular-contact ball bearings made from AISI M-50 steel were fatigue tested with a tetraester and a synthetic paraffinic oil at a bearing temperature of 492 K (425° F) in an air environment. Test conditions include a speed of 12 000 rpm and a thrust load of 25 800 newtons (5800 lb) producing a maximum Hertz stress of 233 000 newtons per square centimeter (323 000 psi) on the bearing inner race. At these conditions bearing life exceeded AFBMA-predicted (catalog) life by factors in excess of 4 and 10 for the tetraester and synthetic paraffinic fluids, respectively.

Under continuous operation with recirculation and no replenishment of the test lubricants, lubricant viscosity increased with time such that the final viscosities after 500 hours operation were 14 and 6 times the initial values for the tetraester and the synthetic paraffinic oil, respectively. This is significantly beyond the viscosity increase generally allowed in aircraft engine operation. However, when the test oil is replaced or replenished at a rate approximating the replenishment rate in actual commercial engines due to normal oil consumption, no significant increase in lubricant viscosity or neutralization number with time was observed in a continuously operating recirculating system with both the tetraester and synthetic paraffinic oils.

In any closely controlled rolling-element bearing study, oil replenishment procedures or system inertion should be utilized, in order to assure that the lubricant viscosity (and neutralization number) remain relatively constant throughout a test.

INTRODUCTION

Advanced airbreathing engines for supersonic aircraft operation are expected to operate with bearing temperatures near 492 K (425° F). In support of these engines, as well as for other high-temperature-oriented bearing applications, a reliable bearing-

* General Electric Company, Cincinnati, Ohio.

lubricant system is required. Over the past decade, several new classes of liquid lubricant have been developed with the aim of extending the upper temperature range of lubricating fluids. These lubricants have been studied to determine their thermal stability characteristics, their oxidation and corrosion properties, their effect on rolling-element fatigue, and their elastohydrodynamic (EHD) film-forming capabilities (refs. 1 to 13). These parameters serve to define the upper-temperature limitations of these fluids.

A high-temperature liquid lubricant which has shown good thermal stability and good EHD film-forming capabilities to 589 K (600° F), is a synthetic paraffinic oil with an antiwear additive (refs. 6 to 11, and 13). This lubricant has provided long bearing life (in excess of 13 times AFBMA life) in full-scale bearing tests at temperatures to 589 K (600° F) in a low oxygen environment (less than 0.1 percent by volume) (refs. 8 to 10). However, the oxidative stability of this lubricant in air and at temperatures as low as 477 K (400° F) is poor (ref. 11).

Another class of lubricants of interest in the temperature range from 477 to 505 K (400° to 450° F) are the advanced type II esters. One such fluid is a tetraester. This lubricant was shown to have potentially good thermal stability at temperatures to 505 K (450° F) (ref. 12). Tests are reported in reference 12 of bearings run at 477 K (400° F) to determine the effects of oxygen concentration on the oxidation of a synthetic paraffinic oil and a tetraester. Under similar test conditions, using a recirculation lubrication system with no oil replenishment, the advanced ester exhibited higher oxidative stability than did the synthetic paraffinic oil. However, a finite time limitation on the effectiveness of oxidation inhibitors in both lubricants was indicated.

The objectives of the research reported herein were (1) to determine the life expectancy with these fluids in large-diameter rolling-element bearings, (2) to establish the lubricating characteristics of a tetraester fluid and a low-viscosity synthetic paraffinic oil in large-diameter rolling-element bearings operating at 492 K (425° F) in air under conditions of speed and maximum load approximating those experienced by a main-shaft bearing in advanced jet engines, and (3) to determine the oxidation characteristics of these fluids with and without oil replenishment at bearing operating times to 500 hours.

Tests were conducted in a high-temperature bearing tester at a temperature of 492 K (425° F) with 120-millimeter-bore angular-contact ball bearings made of consumable-electrode vacuum-melted (CVM) AISI M-50 steel having a Rockwell-C hardness in excess of 60 at a temperature of 492 K (425° F). Test conditions included a speed of 12 000 rpm and a bearing thrust load of 25 800 newtons (5800 lb), which produced a maximum Hertz stress of approximately 223 000 newtons per square centimeter (323 000 psi) on the bearing inner race. Fatigue-life results were evaluated with respect to failure appearance and operating times. Viscosity increase and total neutralization number were used as indicators of lubricant degradation. All tests were conducted by the General Electric Company, Cincinnati, Ohio, under NASA Contract NAS3-11148.

HIGH-TEMPERATURE FATIGUE TESTER

A schematic diagram of the high-temperature fatigue tester is shown in figure 1. The apparatus was initially described in reference 8. In essence, the tester comprises two stationary housings connected by a bellows to form the bearing housing assembly. The rear housing assembly is fixed and contains an auxiliary roller bearing (not shown) to support a test shaft at the drive end, which thus leaves the forward housing assembly free floating.

The two test bearings are mounted on the test shaft and are separated by a shaft sleeve which transmits the axial load between the inner races. The test bearings are retained on the shaft by a bolted retaining plate. The shaft is thus located by the test bearings and has axial freedom through the auxiliary roller bearing.

Loading is accomplished by a system containing 10 springs of 44 482 newtons (10 000 lb) total working capacity. The two test bearings in the housing assembly are axially loaded against each other by the spring system. The load path is from the springs to a circular load plate through a connector to the front plate of the bearing housing assembly. The load is then transmitted to the outer race of the first test bearing and though the shaft sleeve to the inner race of the second test bearing.

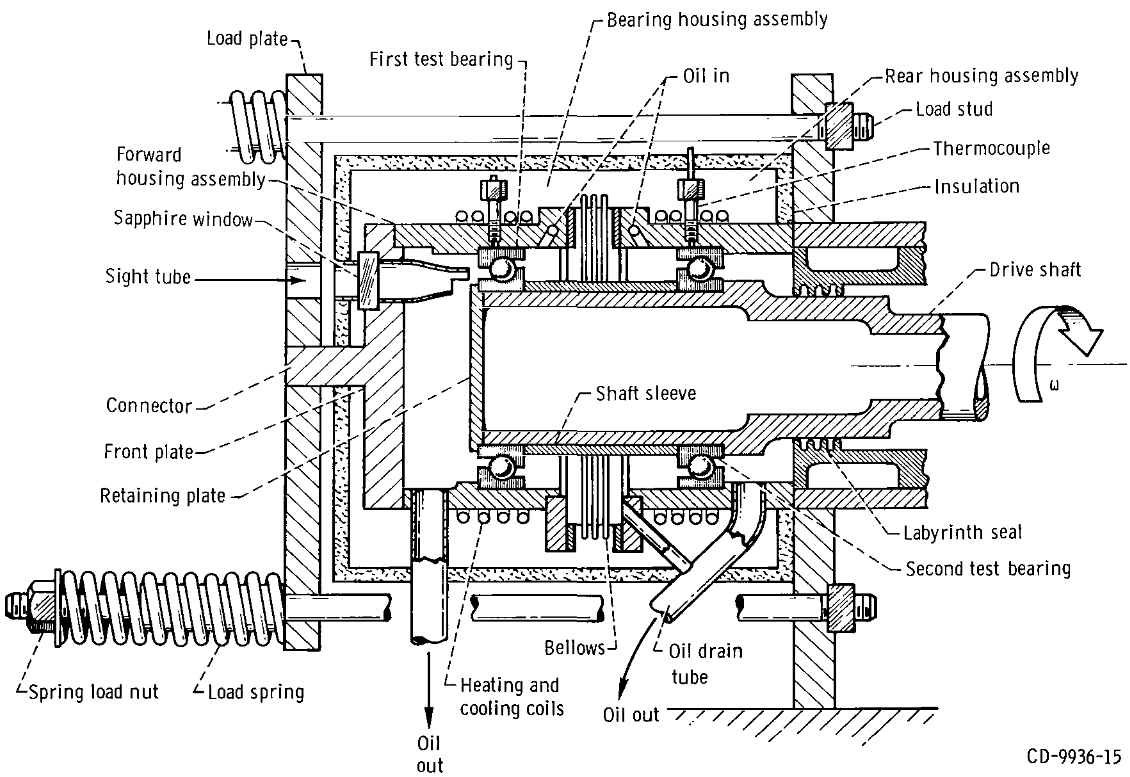

Figure 1. - High-temperature bearing fatigue test apparatus.

Drive of the test apparatus is accomplished by a flat belt on a crowned spindle (not shown) at the auxiliary roller bearing end of the shaft.

Lubrication is provided to the test bearings through a jet-feed lubrication system by a pump immersed in a heated oil reservoir. The reservoir has approximately 11 400 cubic centimeters (3 gal) capacity. The pump is capable of circulating the oil through the system at 190 cubic centimeters per second (3 gal/min) at 589 K (600° F). Gravity drainage for the lubricant is provided by a single exit under each test bearing and also by the bellows in the bearing housing assembly.

Sealing of the oil in the bearing housing assembly from the drive system was provided by a labyrinth seal and a tandem carbon seal (not shown in the schematic diagram). The test shaft was driven at 12 000 rpm. Instrumentation provided for automatic shutoff by monitoring bearing temperature, oil temperature, bearing vibration, flow rate, and pressure. If any of these parameters varied even slightly from those programmed for the test conditions, the test was shut down. An infrared pyrometer was used to measure inner-race temperatures through a sight tube aimed at the inner race of the first test bearing.

TEST BEARINGS

The test bearings were ABEC-5 grade, split inner-race 120-millimeter-bore angular-contact ball bearings having a nominal contact angle of 20°. The inner and outer races were manufactured from one heat of consumable-electrode vacuum-melted (CVM) AISI M-50 steel, and the balls were manufactured from a second heat. The chemical analysis of the M-50 material in this study is given in table I. The nominal hardness of the balls and races was Rockwell C-63 at room temperature. The M-50 has the capability of maintaining a Rockwell-C hardness in excess of 60 at a temperature of 492 K (425° F). This material is currently used by most jet engine manufacturers for high-temperature bearing applications.

Each bearing contained 15 balls, 2.0638 centimeters (13/16 in.) in diameter. The cage was a one-piece outer-land-riding type made of a nickel-base alloy (AMS 4892) having a nominal Rockwell-C hardness of 33. The retained austenite content of the ball and race material was less than 3 percent. The inner- and outer-race curvatures were 54 and 52 percent, respectively. All components with the exception of the cage were matched within ±0.5 Rockwell-C point. This matching assured a nominal differential hardness in all bearings (i.e., the ball hardness minus the race hardness, commonly called ΔH) of zero (ref. 14). The surface finishes were approximately 5×10^{-6} to 7.5×10^{-6} centimeters (2 to 3 μin.) rms on the races and 2.5×10^{-6} to 5×10^{-6} centimeters (1 to 2 μin.) rms on the balls. Bearing test conditions are given in table II.

TABLE I. - CHEMICAL ANALYSIS

OF CONSUMABLE-ELECTRODE

VACUUM-MELTED AISI M-50

BEARING STEEL

Element	Composition, wt. %	
	Races	Balls
Carbon	0.79	0.83
Manganese	.21	.22
Phosphorus	.011	.009
Sulfur	.003	.003
Silicon	.22	.22
Chromium	3.89	3.99
Molybdenum	4.29	4.23
Vanadium	1.00	1.00
Iron	Bal.	Bal.

TABLE II. - TEST CONDITIONS FOR 120-MILLIMETER-BORE ANGULAR-CONTACT BALL BEARING

[Material, AISI M-50 steel; speed, 12 000 rpm.]

Lubricant	Bearing thrust load, N(lb)	Maximum Hertz stress, N/cm^2 (psi)		Temperature, K (°F)				EHD[a] film thickness, cm (μin.)
		Inner race	Outer race	Inner race	Outer race	Oil in	Oil out	
Tetraester	25 800 (5800)	223 000 (323 000)	184 000 (267 000)	492 to 498 (425 to 435)	487 to 498 (415 to 435)	436 to 450 (325 to 350)	470 to 500 (385 to 440)	18.8×10^{-6} (7.5)
Synthetic paraffinic oil	25 800 (5800)	223 000 (323 000)	184 000 (267 000)	492 to 498 (425 to 435)	487 to 498 (415 to 435)	442 to 459 (335 to 365)	478 to 492 (400 to 425)	23.8×10^{-6} (9.5)

[a]Calculated elastohydrodynamic (EHD) film thickness.

TEST LUBRICANTS

Two lubricants were evaluated in an air environment (21-percent oxygen by volume) with the 120-millimeter-bore angular-contact ball bearings made of the AISI M-50 steel. These lubricants were (1) a tetraester (type II) and (2) a synthetic paraffinic oil. A standard ASTM chart showing the viscosity-temperature relation of these fluids is presented in figure 2. Properties of these lubricants are given in table III.

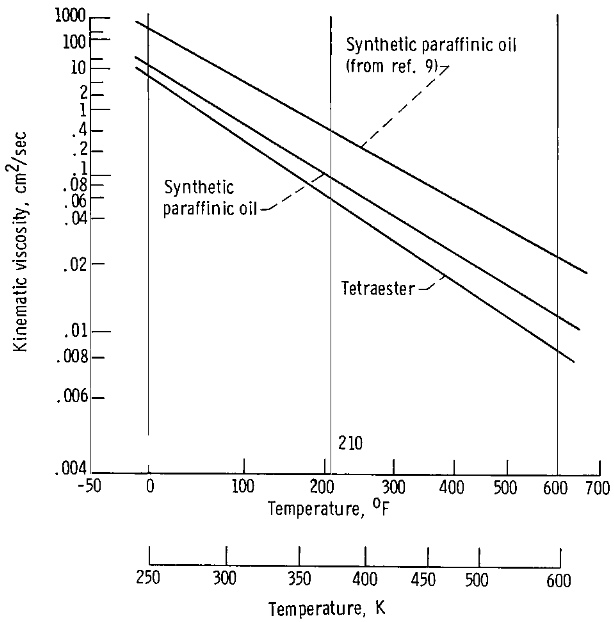

Figure 2. - ASTM chart of lubricant kinematic viscosity as a function of temperature.

TABLE III. - TEST LUBRICANT PROPERTIES

Property	Lubricant description	
	Tetraester	Synthetic paraffinic oil
Additives	Antiwear Oxidation inhibitor Antifoam	Antiwear Oxidation inhibitor
Kinematic viscosity, cm^2/sec, at - 311 K (100° F) 372 K (210° F) 477 K (400° F)	 29×10^{-2} 54×10^{-2} 1.5×10^{-2}	 60×10^{-2} 8.9×10^{-2} 1.9×10^{-2}
Flash point, K (°F)	533 (500)	538 (510)
Fire point, K (°F)	Unknown	575 (575)
Autoignition temperature, K (° F)	718 (830)	645 (700)
Pour point, K (°F)	214 (-75)	225 (-55)
Volatility (6.5 hr at 477 K (400° F)), wt. %	3	Unknown
Specific heat at 477 K (400° F), J/(kg)(K) (Btu/(lb)(ft)(°F))	2340 (0.56)	2810 (0.67)
Thermal conductivity at 477 K (400° F), J/(m)(sec)(K) (Btu/(hr)(ft)(°F))	0.13 (0.075)	0.12 (0.073)
Specific gravity at 477 K (400° F)	0.850	0.721

Tetraester (Type II)

This lubricant is a tetraester-base oil, containing additives which include oxidation and corrosion inhibitors and an antiwear additive. This fluid has shown good operating potential in limited bearing tests at temperatures to 505 K (450° F) in an air environment (ref. 12).

Synthetic Paraffinic Oil

The synthetic paraffinic oil which is a 100-percent paraffinic fluid is of a type which has been extensively tested in previous work (refs. 6 to 11) both with and without an antiwear additive. The fluid used in this investigation is from the same class of fluids previously reported but with a shorter chain length and, hence, a lower fluid viscosity (fig. 2). With the antiwear additive, this lubricant type has shown good thermal stability (ref. 11) and good EHD film-forming capabilities (ref. 13); it has also provided long bearing life at temperatures to 589 K (600° F) in a low oxygen environment.

RESULTS AND DISCUSSION

Fatigue Life Results

Two groups of 120-millimeter-bore angular-contact ball bearings made from consumable-electrode vacuum-melted (CVM) AISI M-50 steel were fatigue tested with a tetraester and a synthetic paraffinic oil at a bearing outer-race temperature of 492 K (425° F). Test conditions included a shaft speed of 12 000 rpm (1.44×10^{6} DN)[1] and a bearing thrust load of 25 800 newtons (5800 lb), which produced a maximum Hertz stress on the bearing inner race of 223 000 newtons per square centimeter (323 000 psi). The fatigue-life results of these tests are shown in figure 3 and are summarized in table IV. For comparison purposes the AFBMA-predicted (catalog) life of these bearings is given in table IV.

The confidence that can be placed in the experimental results was determined statistically by using the methods given in reference 15. The confidence number for the 10-percent life was calculated and is presented in table IV. A confidence number of 84 percent means that 84 out of 100 times bearings lubricated with the synthetic paraffinic oil

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[1]DN is the bearing bore in mm multiplied by the speed in rpm.

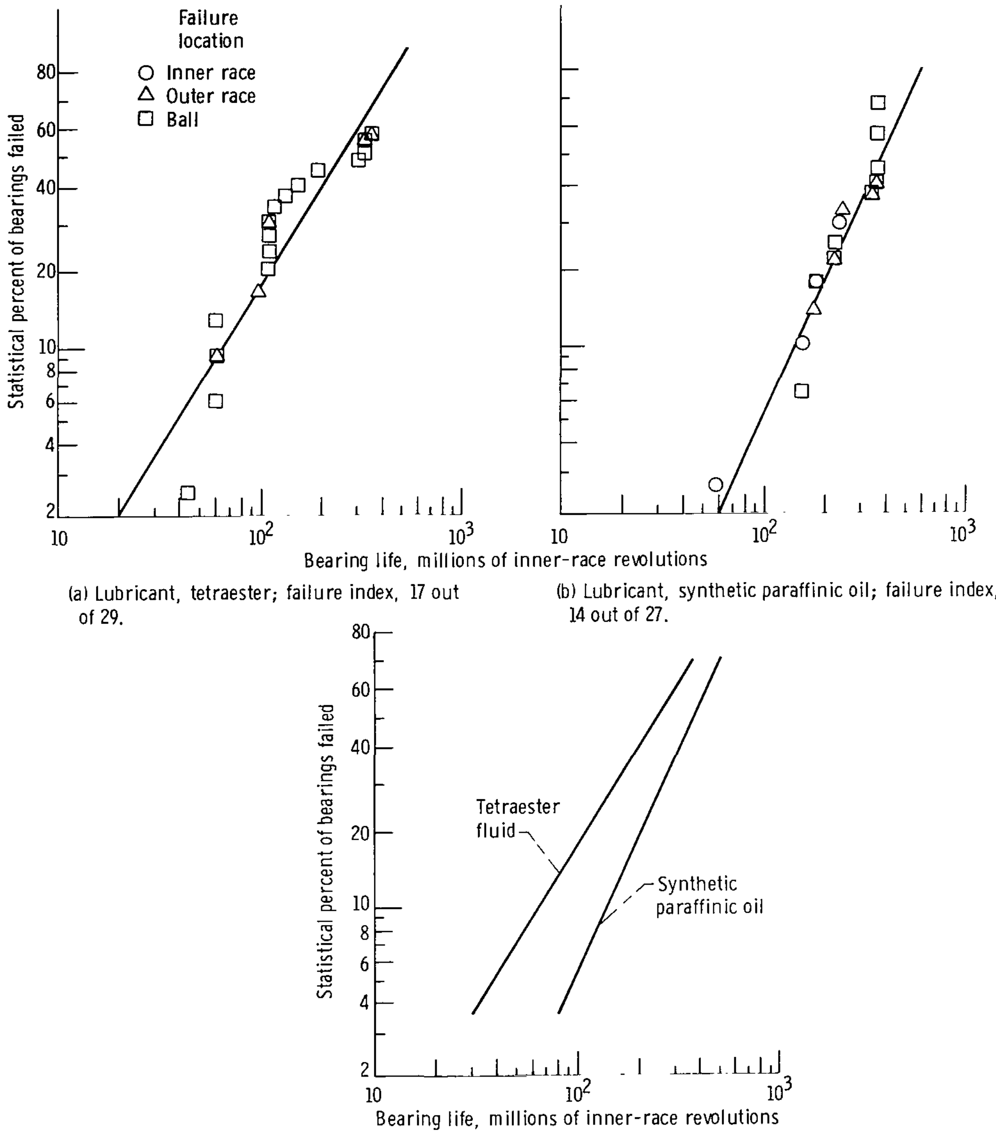

Figure 3. - Rolling-element fatigue life of 120-millimeter-bore angular-contact ball bearings run with two advanced lubricants in air. Thrust load, 25 800 newtons (5800 lb); speed, 12 000 rpm; temperature, 492 K (425° F).

TABLE IV. - FATIGUE-LIFE RESULTS FOR 120-MILLIMETER-BORE ANGULAR-CONTACT BALL BEARINGS MADE FROM CVM M-50 MATERIAL WITH TWO ADVANCED LUBRICANTS AT 492 K (425° F)

[Thrust load, 25 800 N (5800 lbf); speed, 12 000 rpm.]

Lubricant	Experimental life, millions of inner-race revolutions		Weibull slope	Failure index (a)	Confidence number at 10-percent-life level (b)	AFBMA-predicted 10-percent (catalog) life, millions of inner-race revolutions	Ratio of experimental 10-percent life to AFBMA-predicted life
	Ten-percent life	Fifty-percent life					
Tetraester	64	249	1.4	17 out of 29	84	13.4	4.8
Synthetic paraffinic oil	140	380	1.9	14 out of 27	--	13.4	10.4

[a]Number of fatigue failures out of number of bearings tested.

[b]Percentage of time that 10-percent life obtained with tetraester oil will have some relation to the 10-percent life obtained with synthetic paraffinic oil.

will have longer lives than bearings lubricated with the tetraester fluid. Based upon experience, a confidence number of 84 can be considered statistically significant. At 492 K (425° F) in air (21-percent oxygen by volume) the experimental bearing life with the tetraester and the synthetic paraffinic oil exceeded the AFBMA-predicted (catalog) life by factors in excess of 4 and 10, respectively. As a result no derating of bearing life is required with either fluid and the AISI M-50 material combination as a result of elevated-temperature operation.

Metallurgical examination of the bearings indicated that, in the temperature range of 492 K (425° F) with the tetraester and the synthetic paraffinic oil, failure was by classical subsurface fatigue. There was no apparent or measurable wear. However, there were some signs of surface glazing with both lubricants. This observation suggests that at 492 K (425° F) some asperity contact of the mating surfaces occurred. This phenomenon had no apparent effect on the fatigue results. Typical ball and race failures at 492 K (425° F) are shown in figures 4 and 5. Figure 6 shows bearings which had been run with a synthetic paraffinic oil at 492 K (425° F) without failure for more than 500 hours of operation.

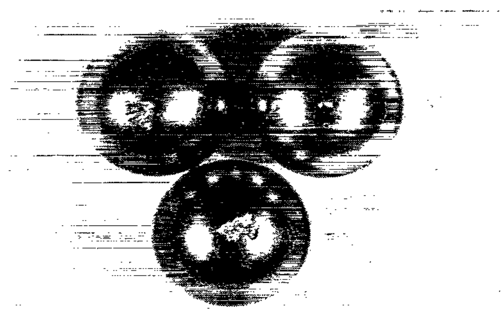

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Figure 4. - Typical fatigue spalls on bearing balls run with synthetic paraffinic oil. Material, AISI M-50 steel; thrust load, 25 800 newtons (5800 lb); speed, 12 000 rpm; temperature, 492 K (425° F); air environment; running time, 304 hours (218×10^6 inner-race revolutions).

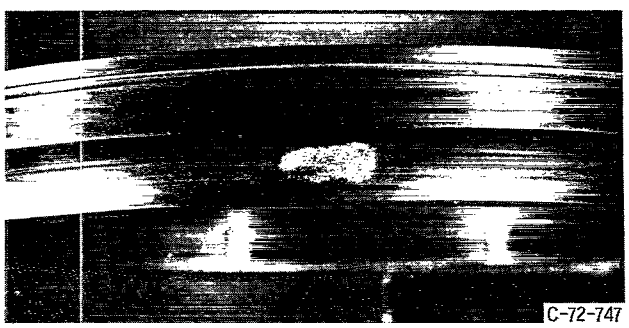

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Figure 5. - Fatigue failure on bearing inner race run with synthetic paraffinic oil. Material, AISI M-50 steel; thrust load, 25 800 newtons (5800 lb); speed, 12 000 rpm; temperature, 492 K (425° F); air environment; running time, 325 hours (234×10^6 inner-race revolutions).

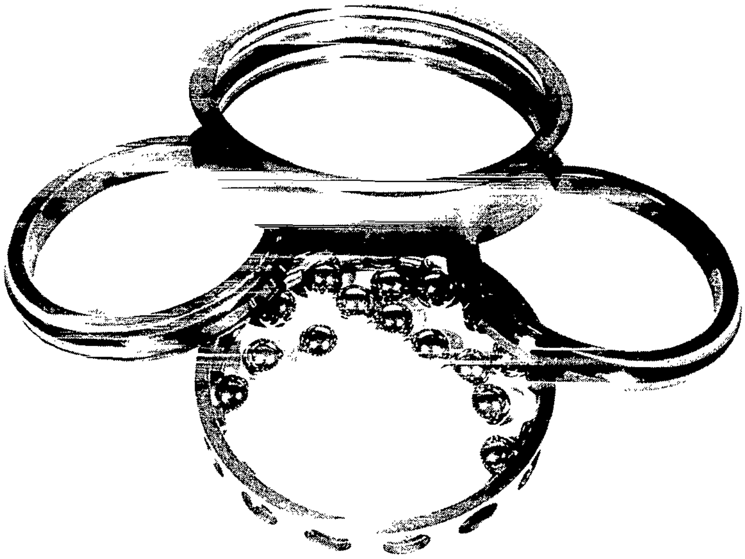

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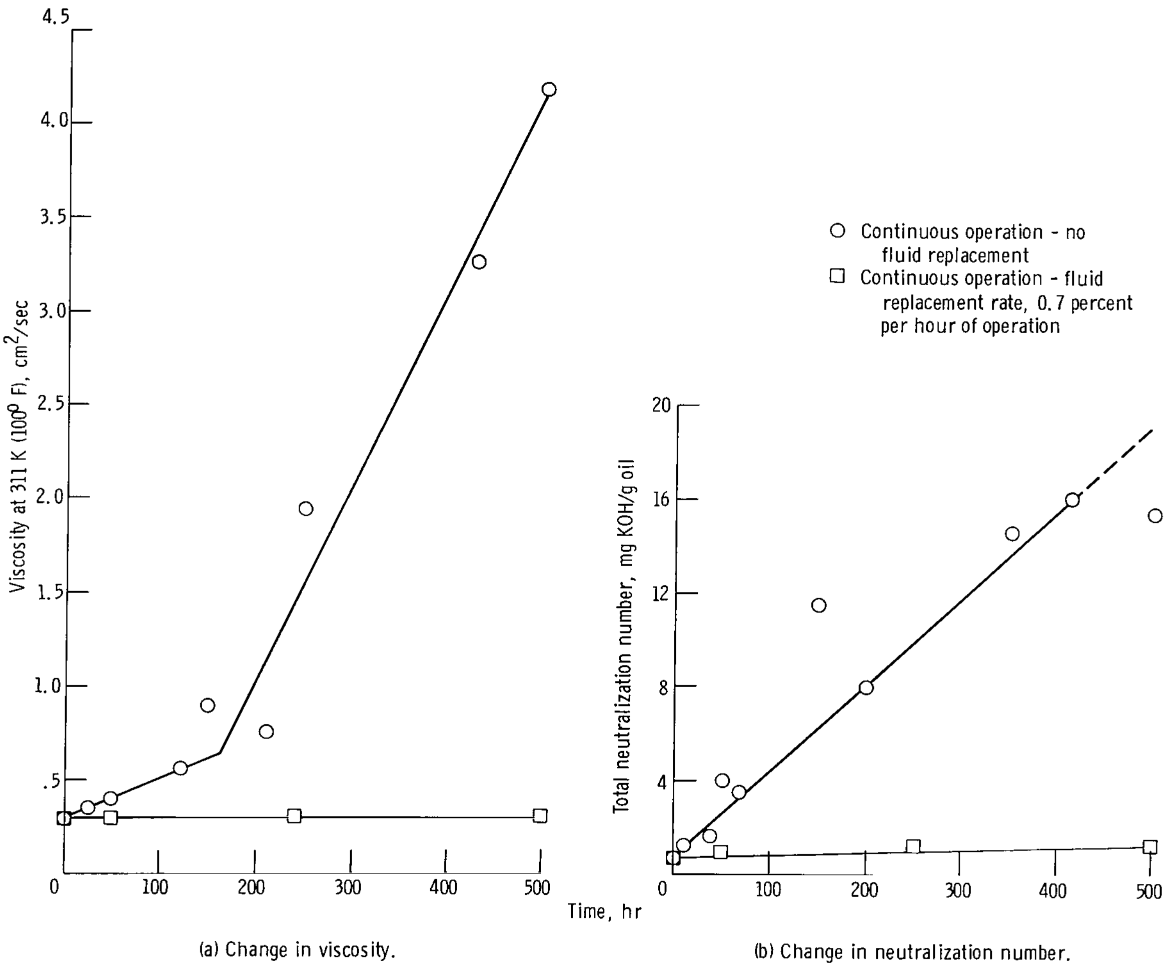
Figure 6. - Unfailed 120-millimeter-bore angular-contact ball bearing run with synthetic paraffinic oil. Material, AISI M-50 steel; thrust load, 25 800 newtons (5800 lb); speed, 12 000 rpm; temperature, 492 K (425° F); air environment; running time, 500 hours (360×10^6 inner-race revolutions).

Effect of Oil Oxidation

In previous testing at elevated temperatures with the synthetic paraffinic fluids (refs. 6 to 10), a low oxygen environment (less than 0.1-percent oxygen by volume) was provided to prevent excessive lubricant oxidation. In current and future aircraft engine applications it is not anticipated that a low oxygen environment will be deliberately designed into the system. However, the displacement of air by lubricant vapors in the bearing sump and the lower partial pressure due to operation at altitude would reduce the moles of oxygen available to react with the lubricant. (At the date of this writing no measurements have been published to indicate the number of moles of oxygen available to react with the lubricant at high-altitude operation.) It can therefore be concluded that the test condition in the bearing tester under atmospheric conditions, with air (21-percent oxygen by volume) at temperatures above 492 K (425° F) is the most severe environment that might be encountered in advanced aircraft engine operation with regard to lubricant degradation.

The fatigue tests for a pair of 120-millimeter-bore angular-contact ball bearings were run continuously with one 0.011-cubic-meter (3-gal) lubricant charge for times in excess of 500 hours with no oil replenishment. (One hundred hours of operation is equivalent to 72 million inner-race revolutions.) The effect of continuous operation with no fluid replacement is shown in figures 7 and 8 for the tetraester and the synthetic paraffinic oil, respectively. Figure 9 compares the percent change in viscosity at 311 K (100° F) for both fluids as a function of time. For the tetraester, viscosity gradually increased with time to approximately twice (100 percent increase) its initial value at 150 hours. At 500 hours the viscosity markedly increases to more than 14 times (1350 percent) its initial value. The same test but with oil replenishment at the rate of approximately 0.7 percent per hour, or 17 percent every 24 hours, showed essentially no change in lubricant viscosity.

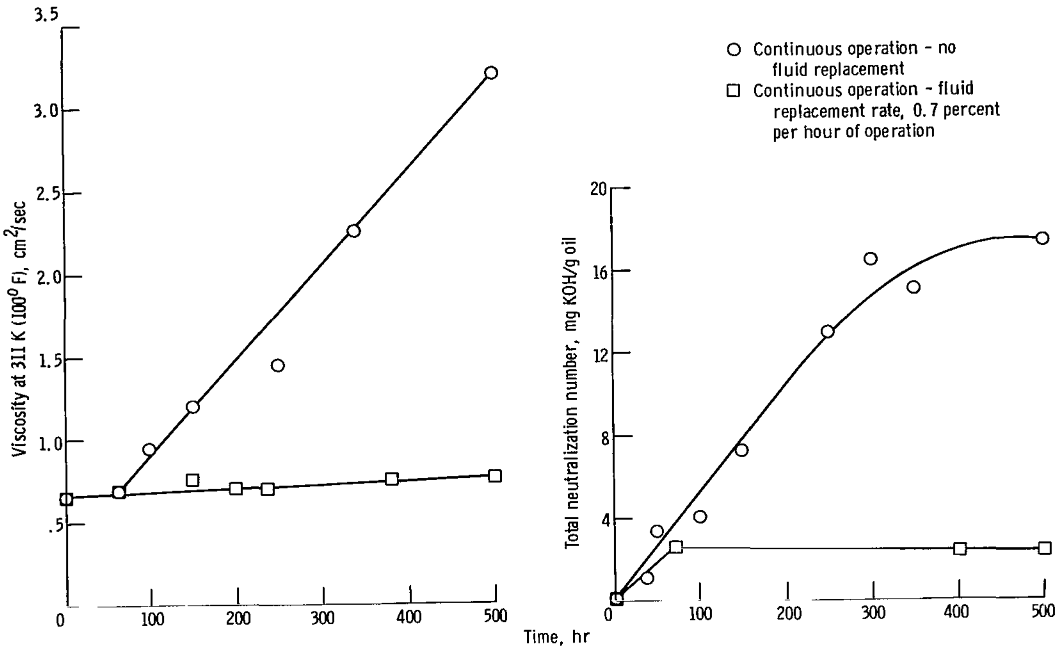
For the tetraester fluid it may be concluded that at the end of 165 hours of operation the oxidation inhibitor contained in the fluid was gradually used up. The change in rate of oxidation as measured by the viscosity change at 165 hours would probably indicate a fluid with no inhibitor. The addition of fluid acted to replenish the oxidation inhibitor and thus prevent any marked increase in fluid viscosity.



(a) Change in viscosity.

(b) Change in neutralization number.

Figure 7. - Effect of oxidation on tetraester fluid run with 120-millimeter-bore angular-contact ball bearings at 492 K (425° F) in air.



(a) Change in viscosity.

(b) Change in neutralization number.

Figure 8. - Effect of oxidation on synthetic paraffinic oil run with 120-millimeter-bore angular-contact ball bearings at 492 K (425° F) in air.

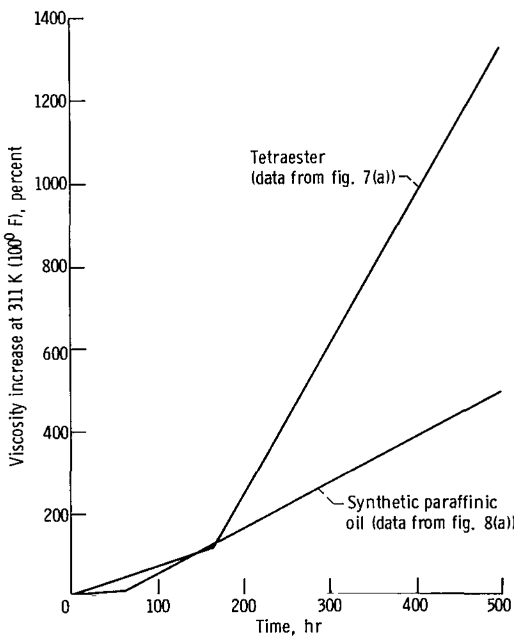


Figure 9. - Comparison of effects of oxidation on tetraester and synthetic paraffinic oil as measured by increase in viscosity under continuous operation with no replenishment.

For the synthetic paraffinic oil there was essentially no change in viscosity for approximately the first 60 hours of operation. Thereafter, the viscosity of the fluid increased to six times (500 percent) its initial value. For the bearing tests with oil replenishment only a slight increase in viscosity occurred for as much as 500 hours of operation. As with the tetraester fluid, the oxidation inhibitor in the synthetic fluid was probably used up at the end of 60 hours of operation without oil replenishment. The replenishment of oil in essence replaced the oxidation inhibitor, thus preventing excessive oil oxidation.

It should be pointed out that the large increases in viscosity and neutralization number where there was no oil replenishment are well above tolerable limits in actual engine operation. While there is no direct specification requirement concerning this matter, it is generally unacceptable when oil viscosity doubles or when neutralization number increases by three to four points.

On the basis of these observations and those of references 11 and 12, it may be concluded that in any closely controlled lubricant-oriented study, oil replenishment procedures or system inertion should be utilized to assure that the lubricant viscosity (and neutralization number) remain constant throughout a test. Were the bearing fatigue tests run with oil replenishment, it is speculated that fatigue lives lower than those reported would be obtained with both fluids. This lower fatigue life would be caused essentially by a lower effective fluid viscosity during operation due to a lack of oxidation. However, based upon the research reported in reference 9, these differences would not be expected to be statistically significant under the test conditions reported.

SUMMARY OF RESULTS

Groups of 120-millimeter-bore angular-contact ball bearings made from AISI M-50 steel were fatigue tested with a tetraester and a synthetic paraffinic oil at a bearing temperature of 492 K (425° F) in an air environment. Test conditions include a speed of 12 000 rpm and a thrust load of 25 800 newtons (5800 lb) producing a maximum Hertz stress of 233 000 newtons per square centimeter (323 000 psi) on the bearing inner race. The results of the tests were as follows:

1. At a temperature of 492 K (425° F) bearing life exceeded AFBMA-predicted (catalog) life by factors in excess of 4 and 10 for the tetraester and synthetic fluids, respectively.

2. Under continuous operation with recirculation and no replenishment of the test lubricants, lubricant viscosity increased with time such that the final viscosities after 500 hours of operation were 14 and 6 times the initial values for the tetraester and the synthetic paraffinic oil, respectively. This is significantly beyond the viscosity increase generally allowed in aircraft engine operation.

3. When the test oil is replaced or replenished at a rate approximating the replenishment rate in actual commercial jet engine usage due to normal oil consumption, no significant increase in lubricant viscosity or neutralization number with time was observed in a continuously operating recirculating system with both the tetraester and synthetic paraffinic oils.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 25, 1972,
132-15.

APPENDIX - ENGINE SIMULATION (MINISUMP TEST)

A laboratory test apparatus termed "minisump," initially described in reference 16, was used to evaluate the lubricants of interest under simulated advanced-engine operating conditions. The apparatus, a schematic of which is shown in figure 10, provides an intermediate test function between the relatively simple, static, lubricant bench tests and the highly complex and expensive full-scale component tests. Furthermore, it achieves, as nearly as possible, a simulation of an actual engine lubrication loop.

As shown in figure 10, the test lubricant is contained in a vented oil reservoir. The lubricant is pumped through a cooler and a static 40-micron filter to a small engine accessory drive gearbox. The fluid leaves the gearbox through an orifice which measures and controls the oil flow. A bypass line immediately before the orifice is used to control oil pressure. Excess oil is returned into one of the scavenge ports of the gearbox. A rotameter continually monitors the oil flow.

The oil passes to an aircraft engine sump. A tape heater is used on the sump inlet oil line to raise the oil temperature to the desired level prior to entering the sump. To

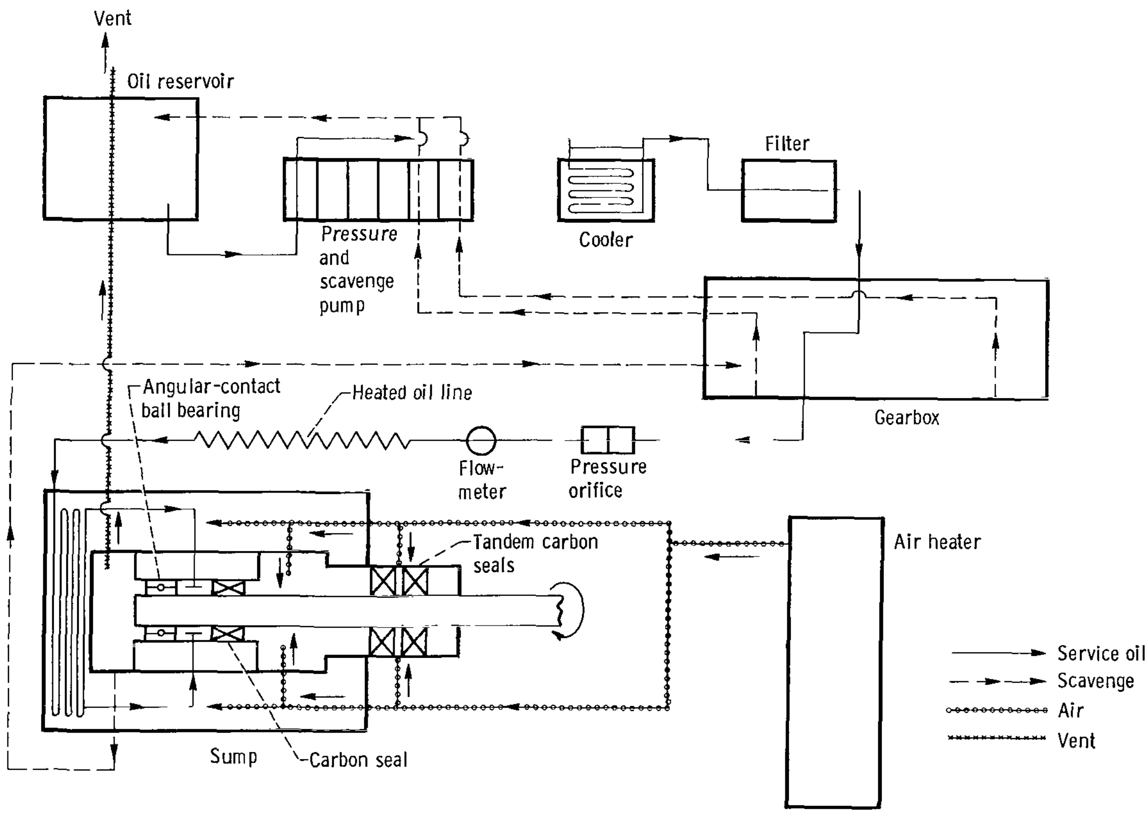


Figure 10. - Minisump flow schematic.

achieve further heating of the oil, several coils of the lubricant line are made in the rear hot-air plenum, which increases the residence time of the oil in the heated environment. The sump contains an 84-millimeter-bore angular-contact ball bearing and a carbon face seal. A separate tandem carbon seal is used to maintain sump pressurization. The oil passes through the sump, acting to cool the carbon seal and to lubricate the bearing, and is then scavenged and returned to the reservoir. Thus, the oil is exposed to the combined thermal and mechanical stresses which it would be expected to encounter in an actual engine.

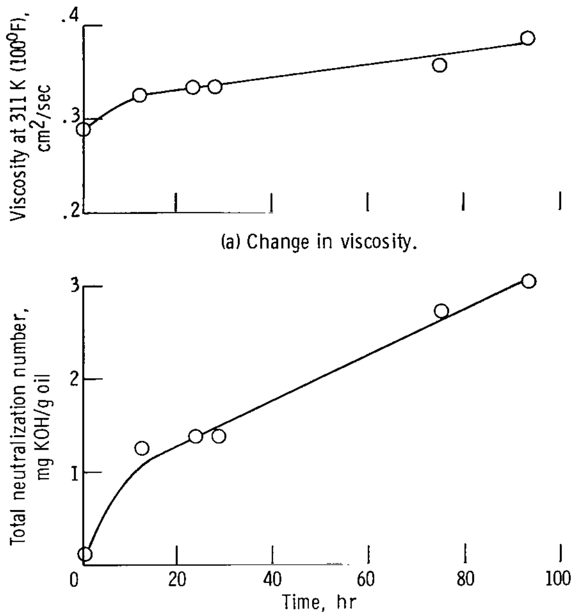
After test lubricant was charged into the 0.0038-cubic-meter (1-gal) capacity oil tank, flow through the system was initiated concurrently with bringing all components to the desired test temperature. The sump is heated by means of a hot-air heater, the effluent of which is circulated in the plenum surrounding the sump (see fig. 10).

Frequent oil samples were taken throughout the duration of the test to establish changes in viscosity and neutralization number. System temperatures, pressures, and oil flows were continually monitored and recorded. Following the test, the apparatus was totally disassembled; and all critical areas were examined for evidence of coke deposits, lubricant effects, and general appearance.

Prior to evaluating the test lubricants in the bearing tester, these lubricants were screened under simulated engine operating conditions in the minisump, as described in the preceding paragraphs. Minisump test conditions are summarized in table V. The results of these tests are shown in figures 11 and 12. In commercial aircraft operation the lubricant is consumed at the rate of approximately 0.7- to 1.0-percent volume per hour of operation due to lubricant leakage and vaporization. In the minisump a similar

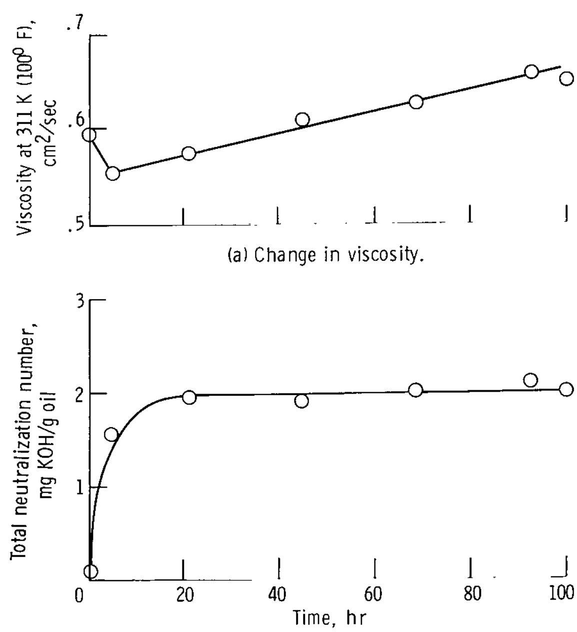
TABLE V. - AVERAGE MINISUMP CONDITIONS

	Tetraester	Synthetic paraffinic oil
Temperature, K (°F) of -		
Sump walls	545 (520)	497 (435)
Oil supply	477 (400)	417 (290)
Oil outlet	505 (450)	477 (400)
Tank	431 (310)	416 (289)
Bearing	508 (454)	492 (425)
Pressurized air	525 (485)	532 (497)
Oil flow rate, cm^3/sec (gal/min)	5.4 (0.085)	5.4 (0.085)
Air flow rate, cm^3/sec (scfm)	1.7×10^4 (0.6)	1.7×10^4 (0.6)
Bearing speed, rpm	4900	4800
Total test time, hr	100	100



(b) Change in neutralization number.

Figure 11. - Effect of oxidation on tetraester fluid under simulated engine operating conditions in a minisump with no fluid replenishment.



(b) Change in neutralization number.

Figure 12. - Effect of oxidation on synthetic paraffinic oil under simulated engine operating conditions in a minisump with no fluid replenishment.

process takes place whereby the oil was removed for sampling at the rate of approximately 0.9-percent volume per hour. In both aircraft and minisump, the oil is replenished when a given volume of oil has been consumed. From the data of figures 7 and 8 for the tetraester and the synthetic paraffinic oil, relatively small changes in neutralization number and viscosity occurred during 100 hours of operation. The minisump results correlate with those of the bearing tests for the same time period of 100 hours.

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