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ROLLING-ELEMENT FATIGUE AND LUBRICATION WITH FLUORINATED POLYETHERS AT CRYOGENIC TEMPERATURES

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ABSTRACT

Paper Entitled

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The lubrication characteristics of four fluorinated polyether lubricants in the temperature range of 160° to 410° R were investigated in a modified five-ball fatigue tester using SAE 52100 steel balls and compared with that of a super-refined mineral oil at room temperature. There was no statistical difference between the fatigue lives obtained with the fluorinated polyether fluid and the super-refined mineral oil at 305° R and 590° R, respectively. This result indicates that at lower temperatures with the polyether, no derating of SAE 52100 in fatigue is necessary. Elastohydrodynamic lubrication was obtained with the fluorinated polyether lubricants at outer-race temperatures from 160° to 410° R, even where outer-race temperatures were lower than the pour points of the fluids. The operating characteristics of the fluorinated polyether fluids at cryogenic temperatures compared favorably with those of the super-refined mineral oil at room temperature.

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Rolling-Element Fatigue and Lubrication with Fluorinated Polyethers at Cryogenic Temperatures

By Marshall W. Dietrich[1], Dennis P. Townsend[1], and Erwin V. Zaretsky[2]

INTRODUCTION

With the forthcoming second generation spacecraft such as large orbiting space stations and reuseable shuttle craft, a need arises for long term operation between overhaul of components, minimum complexity, and extremely high reliability. For most applications which use cryogenic systems such as fuel and oxidizer systems, life support systems, fuel cell systems, and auxiliary power unit systems, the need for reliable bearings has increased greatly. These systems include the short-duration (several minutes) of high-speed rocket turbopumps as well as the long-duration runs (several hundred hours) of cooling system pumps with moderate speeds and loads [1-4][3]. Presently, systems of these types are lubricated by transferring a dry lubricant film from the ball-retainer (cage) pockets to the balls and subsequently to the races of the bearing during operation [5-7]. This "dry transfer-film" method of lubrication provides only boundary lubrication. Wear, therefore, occurs on the rolling elements as well as on the races of the bearing. This wear leads to early failure and relatively short bearing life. In addition, wear in the ball pockets of the retainer can be excessive [5-7], which can lead to premature retainer failure and thus catastrophic failure of the bearing.

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A different approach to the problem of lubrication of cryogenic systems is the use of liquid lubricants. With a liquid lubricant, not only could a higher strength material cage be used but also elastohydrodynamic lubrication would be provided in the rolling-element, race contact. Wear on the balls, races, and retainer would be minimized. It is, therefore, probable that bearings could have much longer lives at cryogenic temperature than now achieved.

A lubricant capable of forming an elastohydrodynamic film in cryogenic applications must be liquid in the cryogenic temperature range. It must also be able to operate at the maximum system temperature without evaporation. The fluid should be chemically inert and not be susceptible to water absorption, which may cause corrosion of the bearing components. In addition, good heat-transfer properties are desirable.

A class of fluids which exhibits many of the properties required for cryogenic applications is the fluorinated polyethers [8-9]. While some of the fluid properties such as viscosity and heat-transfer characteristics are clearly defined, the ability of the fluid to provide adequate lubrication needs to be determined experimentally.

In addition to the above, at cryogenic temperatures, the bearing materials used such as AISI 440C stainless steel and SAE 52100 increase in hardness as the temperature decreases. As a result, phase changes can occur in these materials which may or may not be detrimental to the fatigue life of the rolling-element system. Additionally, it is known that, in general, fatigue life increases with increasing hardness [10-11].

As temperatures decrease the hardness of the components increases and, thus, fatigue life may increase.

The research reported herein, which is based on the work reported initially in [12], was undertaken to investigate the performance of four fluorinated polyether fluids in a modified five-ball fatigue tester using consumable-electrode vacuum-melted (CVM) SAE 52100 ball specimens at temperatures from 160° to $410^{\circ}R$. The objectives were (a) to compare the lubricating characteristics of fluorinated polyether fluids at cryogenic temperatures to those of a mineral oil at room temperature, (b) to determine the effect of fluid viscosity, maximum Hertz stress, and contact angle on the system temperature, and (c) to determine the fatigue life of SAE 52100 steel ball specimens at $590^{\circ}R$ and $305^{\circ}R$. All ball specimens were from the same heat of material and each fluid of a specific viscosity was from the same lubricant batch.

APPARATUS

The five-ball fatigue tester used in this investigation is shown schematically in figures 1(a) and (b) and was previously described in [13]. Essentially, this fatigue apparatus consists of a half-inch diameter test ball which is pyramided upon four half-inch diameter lower test balls that are positioned by a separator and free to rotate in an angular contact race way; see figure 1(b).

The upper test ball is analogous in operation to the inner race of a ball bearing, while the lower test balls in the angular contact race way are analogous to the balls in a bearing. For every revolution of the drive shaft, the upper test specimen receives three stress cycles. Instrumentation provides for automatic failure detection and shutdown. Lubrication for the tests herein described was completely provided by submerging the five ball assembly in the lubricating fluid.

This apparatus was modified for the cryogenic tests as shown in figure 1(c). An annular vacuum jacketed dewar was provided around the test block. In this application, the liquid nitrogen acts as an infinite heat sink with a temperature of 140°R. The lubricating fluid in which the five ball assembly is immersed acts as both a heat transfer medium and a lubricant.

The lower test block, which is constructed of stainless steel, is covered with a layer of polystyrene foam for additional insulation against undue heat leakage from the environment. The sources of heat within the test block region are the heat leaks down the shaft, heat generation due to the rolling and sliding contacts, and heat generation due to the viscous shearing of the lubricant in the test chamber.

The apparatus temperature is controlled by two proportional controllers in series. One senses the outer-race temperature, and the other, the liquid nitrogen level in the dewar. This allows continuous unattended running at a given outer race and lubricant temperature. In addition, the temperature of the upper ball is monitored by a thermocouple embedded in the ball center. An axial hole was drilled through the drive spindle to insert the thermocouple wire. The thermocouple EMF was taken out through a slip-ring-brush assembly mounted at the top end of the drive spindle. The fluid temperatures are measured at two stations within the test cavity at radial distances approximately one-quarter inch apart.

MATERIALS, LUBRICANTS, AND PROCEDURE

Test Lubricants - The test lubricants evaluated were a family of fluorinated polyethers having the general formula

$$F(\underset{\underset{CF_3}{\downarrow}}{CF}CF_2O)_nCHFCF_3$$

where N = 1, 2, 3, or 4.

Four fluids with different viscosities were evaluated. These fluids are designated E1, E2, E3, and E4. Subscript N represents the degree of polymerization of the polymer so that at a given temperature, the viscosity of the lubricant increases as the degree of polymerization increases. The fluorinated polyether lubricant properties are summarized in Table 1. The viscosities of the lubricant as functions of temperature are shown in figure 2.

The fluorinated polyether lubricants were compared with a super-refined naphthenic mineral oil at 130°F. Table 2 gives the properties of this lubricant.

Test Procedure - The test specimens were half-inch diameter SAE 52100 steel balls with a nominal Rockwell C hardness of 61 at room temperature. The balls were thoroughly cleaned by immersion in a 95% ethyl alcohol solution. They were removed from the cleaning solution and air dried. The balls were inserted in the test block, and enough lubricant was added to entirely cover the five ball assembly. The axial load was applied to the five ball system. Liquid nitrogen was added to the dewar to cool the system to operating temperature. As the outer race temperature reached 385° R, the drive motor was started, a drive shaft speed of 4750 rpm was maintained. Temperatures were measured at half-hour intervals and the tests continued until a thermal equilibrium was reached in the system (i.e., until two successive temperature readings showed no change). The average test duration was about two hours.

Running track profiles of randomly selected upper test balls were obtained to determine wear and deformation. These measurements were compared with measurements taken from specimens run under similar load and speed conditions with the super-refined mineral oil at 590° R(130° F).

Rolling-element fatigue tests were conducted with the E-1 fluorinated polyether fluid at 305° R(-155° F). The results were compared with fatigue tests obtained previously with a super-refined mineral oil at 590° R(130° F).

RESULTS AND DISCUSSION

In order to determine the operating characteristics at cryogenic temperatures of the four fluorinated polyether fluids with different viscosities, the upper-ball temperature as a function of ball-spin velocity in an upper ball, lower-ball contact is shown in figure 3 for a constant outer-race temperature of 260° R and a constant maximum Hertz stress of 800,000 psi. These data show that, at a constant outer-race temperature, the upper ball temperature increases slightly if contact angle (ball-spin velocity) increases. This result is not unexpected since an increase in ball-spin velocity generates more frictional heat in the contact zone, thereby raising the temperature.

These results are thus a qualitative indication of the heat being generated in a five-ball fatigue tester as a result of changes in contact angle.

A plot of upper-ball temperature as a function of the lubricant temperature is shown in figure 4 for the four fluids at the four contact angles. Representative data points are shown for the 10° contact angle and are omitted for the 20, 30 and 40 degree angles because of space limitations. No difference in temperature occurred between the two locations at which the lubricant temperature was measured. This plot indicates that, for all four lubricants, the upper-ball temperature varied linearly with the lubricant temperature. All showed the same rate of change. From these results, the relation between lubricant temperature, T_{LUB} and upper-ball temperature, $T_{UPPER\ BALL}$ expressed in degrees R can be written as follows:

$$T_{UPPER\ BALL} = T_{LUB} + C$$

where $C = 19^{\circ}R$ for 10° contact angle

$C = 33^{\circ}R$ for 20° contact angle

$C = 40^{\circ}R$ for 30° contact angle

$C = 40^{\circ}R$ for 40° contact angle

From these equations, the upper-ball temperature can be predicted without the added complexity of directly measuring the temperature of the rotating body.

The lubricant temperature and the upper-ball temperature are plotted as functions of the outer race temperature in figures 5 and 6, respectively. Here again data points for fluids E-1 are given as representative of the other data presented. For each of the lubricants, there is an outer-race temperature range wherein both the lubricant and the upper-ball temperature remain relatively constant as the outer-race temperature increases. This range is coincident with a temperature range up to and including the pour point for each of the fluids. After the outer-race temperature reaches the lubricant pour point, both the lubricant and the upper-ball temperatures increase at a relatively constant rate. This phenomenon can be best explained by initially considering the bulk lubricant to be below the pour point. The outer-race temperature is also below the pour point temperature. The fluid near the rolling elements is subsequently heated by viscous shearing and stabilizes at a temperature well above its pour point. In this condition, the system heat generation stabilizes, and the upper-ball and the bulk lubricant temperatures remain relatively constant. Thus, sufficient lubrication is provided at outer-race temperatures below the fluid pour point. When the outer-race temperature is above the pour point temperature, the total lubricant volume can circulate in the reservoir. Therefore, the temperature of the lubricant and the upper-ball begin to increase as the outer-race temperature increases.

The upper-ball temperature is plotted as a function of the maximum Hertz stress in the upper-ball, lower-ball contact in figure 7. For the four fluorinated polyether lubricants tested, the upper-ball temperature increased with increasing maximum Hertz stress. The rate of increase for these data is approximately 5°R per 100,000 psi maximum Hertz stress in the range between 500,000 and 800,000 psi. Comparative data for the super-refined naphthenic mineral oil at 510°R and the fluorinated polyether at 310°R are shown in figure 8. The rate of temperature increase is approximately the same for both lubricants. In both cases, the outer-race temperature was maintained constant.

In figure 9, the profile trace of a typical test specimen running track lubricated with the fluorinated polyether lubricant at 345°R is compared with that of the representative specimen lubricated with the super-refined mineral oil at 130°F (590°R). This mineral oil is known to provide elastohydrodynamic lubrication under the conditions indicated.

Rolling contact under these conditions (figure 9) results in an alteration of the rolling-element surfaces. This effect manifests itself in 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. The representative trace for the specimen run with the fluorinated polyether (figure 9(b)) shows that the permanent deformation was approximately the same as that obtained with the mineral oil (figure 9(a)). However, the amount of wear appears to be somewhat less. This indicates that the fluorinated polyethers used as lubricants in the range of 160° to 410°R are comparable with a mineral oil lubricant at moderate temperatures 560° to 760°R. Thus, it can be concluded that the fluorinated polyether lubricants can form elastohydrodynamic films at the cryogenic temperatures tested.

In addition to lubrication factors, which can effect life of the rolling-element system, material factors are also a consideration.

Hardness is an important parameter. Generally, as hardness is increased, rolling-element fatigue life is also increased, although not necessarily commensurate with the increase in hardness. As temperature of a material is decreased, hardness is increased. In addition, there is a tendency for the retained austenite in the material to transform to martensite. It has been speculated by many that austenite is detrimental to rolling-element fatigue life [14]. However, there has been no actual experimental evidence to substantiate this phenomena. At cryogenic temperatures most of the retained austenite should be transformed to martensite. In addition, the applied stress influences the martensitic transformation. The amount of martensite formed increases with larger strains and with lower temperatures. However, lowering the temperature does not necessarily lead to more complete transformation because suppression at very low temperatures may result. This suppression, associated with hardening of the austenitic phase is called mechanical stablization. There is no work in the open literature which reports on these characteristics for SAE 52100 steel.

A hardness tester modified for cryogenic testing was used to determine the hardness of SAE 52100 as a function of temperature. A schematic of the tester is shown in figure 10. The results of these tests are shown in figure 11. It can be seen that as temperature decreases, the hardness increases approximately one point Rockwell C for every 100°R decrease in temperature.

Rolling-element fatigue tests were conducted with the E-1 fluorinated polyether at 305°R. The results of these tests are shown in figure 12. Also shown in figure 12 are the results of fatigue tests run with a super-refined naphthenic mineral oil [15]. All of the test conditions for the two test series were identical except for the test temperatures and the lubricant viscosities. The fluorinated polyether was run at 305°R and had a kinematic viscosity of 10 centistokes. The super-refined naphthenic mineral oil was run at a temperature of 590°R and had a kinematic viscosity of 37 centistokes. The accepted relation between fatigue life L and lubricant viscosity μ is $L = K\mu^n$, where K is a constant and n equals 0.2 to 0.3 [16, 17]. Using the above relation and n = 0.25, the life obtained in [15] with the mineral oil at 37 centistokes was adjusted to a theoretical life obtainable at a viscosity value of 10 centistokes. This adjusted life distribution for the mineral oil is shown as the broken line in figure 12.

The confidence that can be placed in the experimental results was determined statistically using the methods given in [18]. The confidence number calculated for the data of figure 12 was 70 percent. The confidence number indicates the percentage of the time that the 10-percent life obtained with each series of tests will have the same relation. Thus, a confidence number of 70 percent means that 70 out of 100 times the specimens tested at the cryogenic condition will be ranked relative to the mineral oil as shown in figure 12. For statistical purposes this confidence is considered insignificant to conclude that there is any difference in early life between the mineral oil and the fluorinated polyether. A 68-percent confidence is approximately equal to a one-sigma deviation.

It can be seen from figure 12 that at the 10-percent life level, the life with the mineral oil is approximately 45 percent less than that obtained with the E-1 fluid. Based on figure 11 and the following equation 11

$$\frac{L_2}{L_1} = e^{m(Rc_2 - Rc_1)}$$

where m = 0.1

L_2 = the life at Rc_2

L_1 = the life at Rc_1

it would be expected that a 22 percent increase in life with the mineral oil can occur with the decrease in upper-ball temperature from 590°R to 345°R (fluid temperature 590°R and 305°R respectively) based on material hardness alone. While the experimental difference is not statistically significant, it can be accounted for by the increased hardness of the SAE 52100 at the cryogenic temperature. What is important is that there is no need to derate the SAE 52100 steel in fatigue for applications in the cryogenic temperature range with the fluorinated polyether lubricants. However, where this fluid is to be used in a cryogenic system, the engineer must consider the added complexity of separate lubrication and seal systems.

SUMMARY

The lubrication characteristics in four fluorinated polyether lubricants in the temperature range of 160° to 410°R were investigated in a modified five-ball fatigue tester with SAE 52100 steel balls.

The lubricating characteristics of the fluorinated polyether fluids at the cryogenic temperature range were compared with those of a super-refined naphthenic mineral oil at 590°R (130°F). The effect of fluid viscosity, maximum Hertz stress, and contact angle on the system temperature was determined. Fatigue data were obtained with the fluorinated polyether lubricant at 305°R and the synthetic paraffinic oil at 590°R. These temperatures provided the same fluid viscosity at test temperature. The following results were obtained:

1. There was no statistical difference between the fatigue lives obtained with the fluorinated polyether fluid and the super-refined mineral oil at 305°R and 590°R, respectively. This result indicates that at lower temperatures with the polyether fluid, no derating of SAE 52100 in fatigue is necessary.

2. Elastohydrodynamic lubrication was obtained with the fluorinated polyether lubricants at outer-race temperatures from 160° to 410°R, even where outer-race temperatures were lower than the pour points of the fluids.

3. The operating characteristics of the fluorinated polyether fluids at cryogenic temperatures compared favorably with those of the super-refined mineral oil at room temperature.

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TABLE 1 - PROPERTIES OF FLUORINATED POLYETHER LUBRICANTS[a]

General formula for family of fluorinated polyethers: $F(\underset{\displaystyle CF_3}{\underset{\vert}{CF}}CF_2O)_nCHFCF_3$	Fluid designations			
	E-1	E-2	E-3	E-4
	Degree of polymerization of polymer			
	n = 1	n = 2	n = 3	n = 4
Molecular weight	286.03	452.08	618.12	784.15
Boiling point: °R	562	673	767	839
Compressibility at 537°R and 500 atm, percent	8.20	6.48	5.64	5.18
Heat of vaporization at boiling point: Btu/lb	[b]41.4	[b]31.3	[b]26.1	[b]22.5
Approximate pour point (200,000 cs °R	214	270	300	322
Density: (At 77°F) lb/gal	13.2	13.8	14.3	14.7
Specific heat, C_p: Btu/(lb)(°R)	[b]0.245	0.244	0.243	[b]0.241
Thermal conductivity: Btu/(hr)(ft)(°R)	[b]0.05	[b]0.05	[b]0.05	[b]0.05
Thermal expansion: $ft^3/(lb)(°R)$	10×10^{-6}	8.5×10^{-6}	6.5×10^{-6}	6×10^{-6}
Vapor pressure at 585°R: psia	23.7	2.03	0.23	0.082
Viscosity at 537°R: cs	0.3	0.6	1.3	2.3

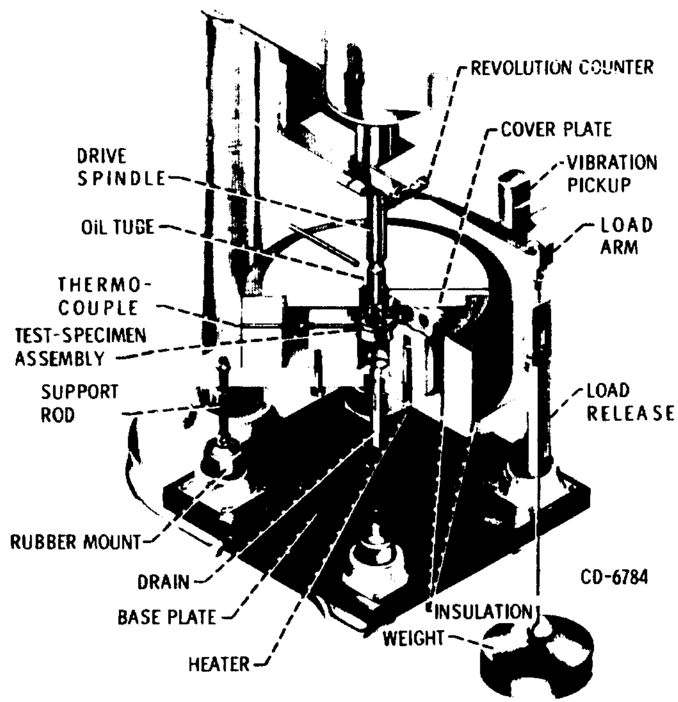
[a] From ref. 8.
[b] Estimated values.

TABLE 2 - PHYSICAL PROPERTIES OF

SUPER-REFINED NAPHTHENIC MINERAL OIL

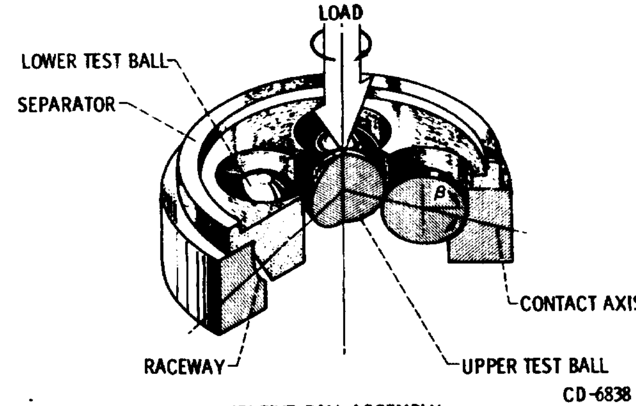
(Manufacturer's data)

Density, g/cu cm, at -	
0°F	0.908
77°F	.880
100°F	.873
200°F	.838
300°F	.802
400°F	.768
500°F	.732
Vapor pressure (extrapolated), mm of Hg, at -	
125°F	$<10^{-5}$
300°F	.07
400°F	2.0
500°F	17.0
Viscosity, cs, at -	
0°F	10,000
30°F	1,500
77°F	155
100°F	79
210°F	8.4
500°F	1.1
700°F	.6
Cleveland open cup flash point, °F	445
Cleveland open cup fire point, °F	495
ASTM pour point, °F	-30



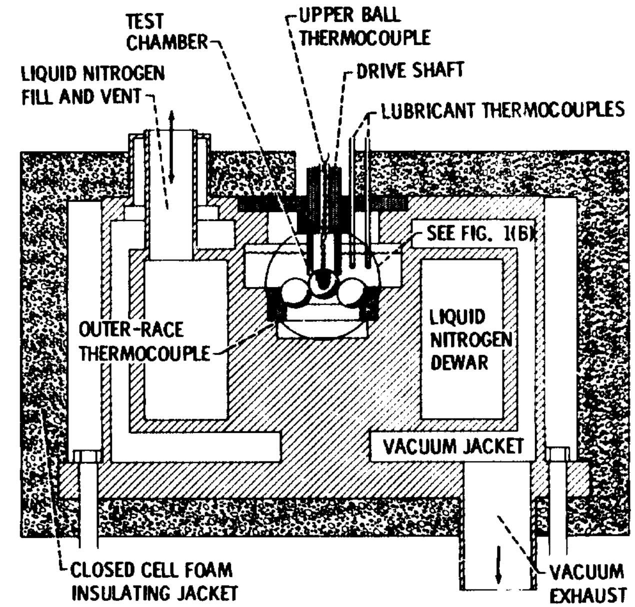
(A) STANDARD FIVE-BALL-FATIGUE TESTER.

Figure 1. - Test apparatus.



(B) FIVE-BALL ASSEMBLY.

Figure 1. - Continued.



(C) SIMPLIFIED CROSS SECTION OF LOW TEMPERATURE FIVE-BALL FATIGUE TESTER.

Figure 1. - Concluded.

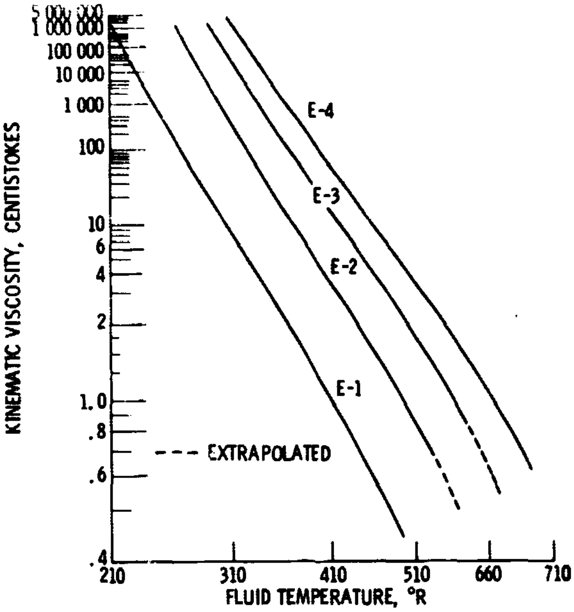


Figure 2. - Temperature-viscosity relationship for the fluorinated polyether lubricants (from ref. 8).

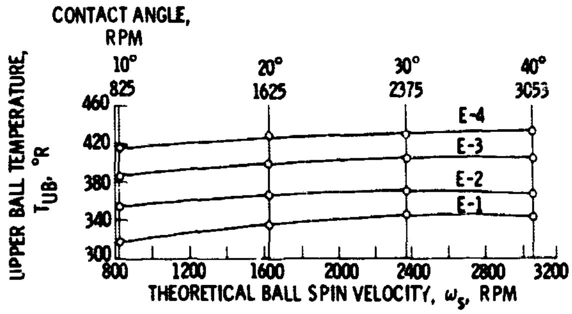


Figure 3. - Upper ball temperature as a function of theoretical ball spin velocity for a constant outer race temperature of 260° R and a constant maximum Hertz stress of 800 000 psi. Lubricant, E-1, E-2, E-3, E-4; shaft speed, 4750 rpm.

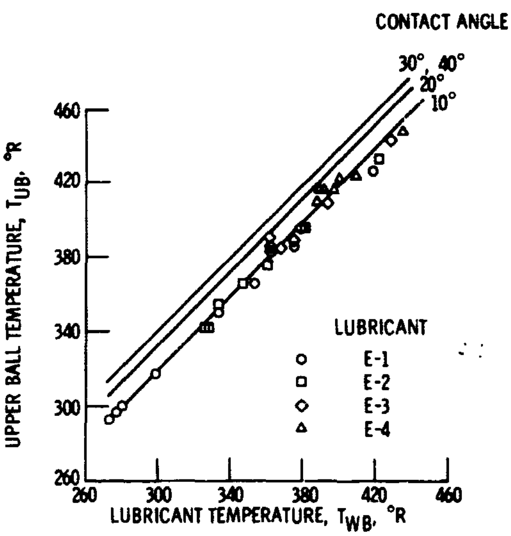


Figure 4. - Upper ball temperature as a function of lubricant temperature. Shaft speed, 4750 rpm, maximum Hertz stress, 800 000 psi

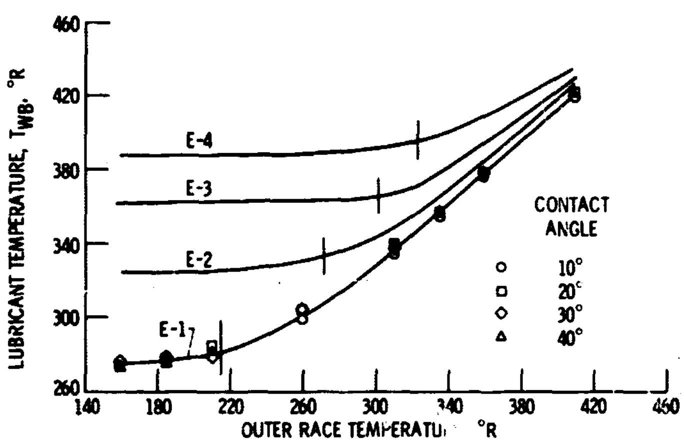


Figure 5. - Lubricant temperature as a function of outer race temperature. Shaft speed, 4750 rpm; maximum Hertz stress, 800 000 psi.

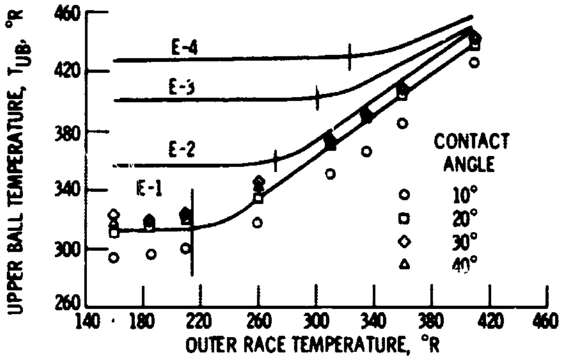


Figure 6. - Upper ball temperature as a function of the outer race temperature. Shaft speed 4750 rpm; maximum Hertz stress, 800 000 psi.

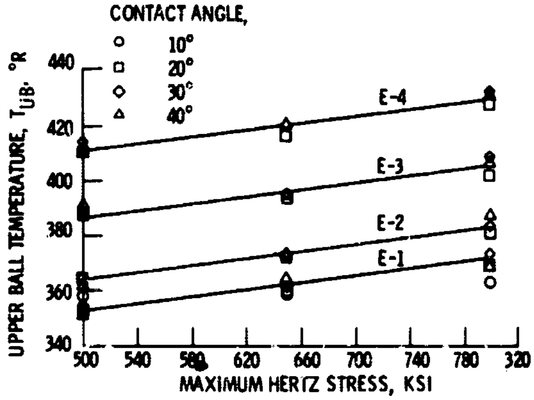
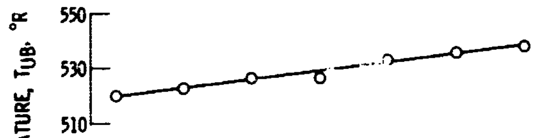
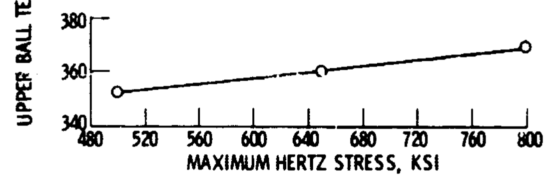


Figure 7. - Upper ball temperature as a function of maximum Hertz stress for a constant outer race temperature of 310° R. Lubricant, E-1, E-2, E-3, E-4; contact angle, 10°, 20°, 30°, 40°; shaft speed, 4750 rpm.

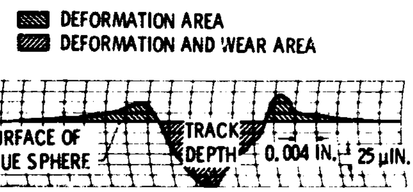


(A) LUBRICANT, SUPER-REFINED MINERAL OIL; SHAFT SPEED, 4750 RPM; OUTER RACE TEMPERATURE, 510° R.

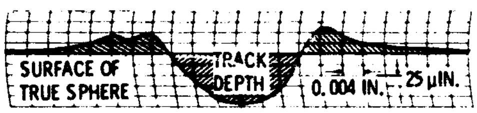


(B) LUBRICANT, E-1; SHAFT SPEED, 4750 RPM; OUTER RACE TEMPERATURE, 310° R.

Figure 8. - Upper ball temperature as a function of maximum Hertz stress.



(A) LUBRICANT, SUPER-REFINED MINERAL OIL; SHAFT SPEED, 4900 RPM; RUNNING TIME, 22 HOURS; BALL TEMPERATURE, APPROXIMATELY 590° R.



(B) LUBRICANT FLUORINATED POLYETHER; SHAFT SPEED, 4750 RPM; RUNNING TIME, 19 HOURS; BALL TEMPERATURE, 345° R.

Figure 9. - Magnified running track profiles of 1/2-inch-diameter SAE 52100 steel upper-test ball specimens. Contact angle, 20°; maximum Hertz stress, 800 000 psi.

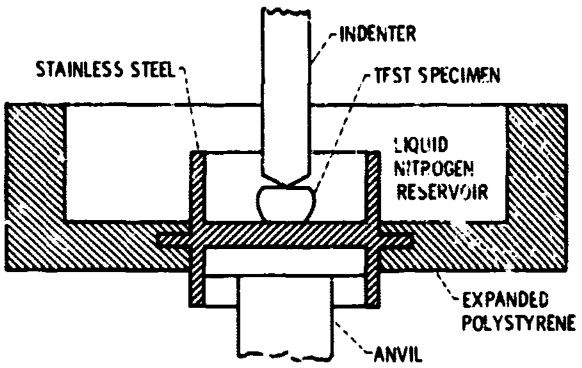


Figure 10. - Cross sectional view of cryogenic hardness testing fixture.

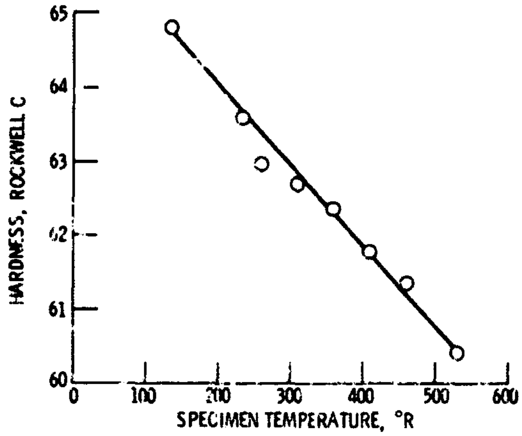


Figure 11. - Test ball hardness as a function of temperature.

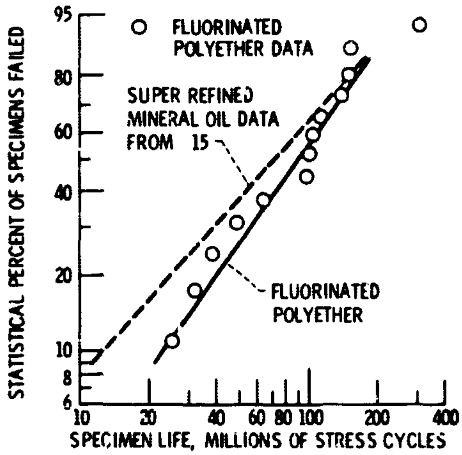


Figure 12. - Rolling element fatigue life of SAE 52100 steel. Speed, 4750 rpm; maximum Hertz stress, 800 000 psi; contact angle 20°; Lubricants, a super-refined naphthenic mineral oil at 590° R and fluorinated polyether at 305° R.