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EFFECT OF VISCOSITY ON ROLLING-ELEMENT FATIGUE LIFE AT CRYOGENIC TEMPERATURE WITH FLUORINATED ETHER LUBRICANTS

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Rolling-element fatigue tests were conducted with 12.7-mm- (1/2-in.-) diameter AISI 52100 steel balls in the NASA five-ball fatigue tester, with a maximum hertz stress of 5500 mN/m^2 (800 000 psi), a shaft speed of 4750 rpm, lubricant temperature of 200 K (360° R), a contact angle of 20°, using four fluorinated ether lubricants of varying viscosities. No statistically significant differences in rolling-element fatigue life occurred using the four viscosity levels. Elastohydrodynamic calculations indicate that values of the lubricant film parameter Λ were approximately 2 or greater.

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SUMMARY

Rolling-element fatigue tests were conducted with 12.7-millimeter- (1/2-in.-) diameter AISI 52100 steel balls in a NASA five-ball fatigue tester. Tests conditions were a maximum Hertz stress of 5500 meganewtons per square meter (800 000 psi), a shaft speed of 4750 rpm, a lubricant temperature of 200 K (360° R), a contact angle of 20°. The four lubricants used were from a family of fluorinated ethers referred to as E-1, E-2, E-3, and E-4. Their viscosities at the lubricant test temperature were 2.2×10^{-6}, 15.4×10^{-6}, 150.0×10^{-6}, and 1600.0×10^{-6} square meter per second (2.2, 15.4, 150.0, and 1600.0 cS), respectively. No statistically significant differences in the rolling-element fatigue life occurred using the four viscosity levels. Elastohydrodynamic calculations indicate that values of the lubricant film parameter Λ were approximately 2 or greater with the possible exception of the lowest viscosity level.

INTRODUCTION

Bearings which are run in cryogenic environments are often lubricated by transferring a dry lubricant film from the retainer pockets to the balls (or rollers) and subsequently to the races of the bearing during operation (refs. 1 to 3). 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 generally leads to early failures and relatively short bearing life. In addition, wear in the ball pockets of the retainer can be excessive (refs. 1 to 3) which can lead to premature retainer failure and thus catastrophic failure of the bearing.

A different approach to the problem of lubrication in cryogenic systems was reported in references 4 to 6. Fluorinated ethers (refs. 7 and 8) were used as a liquid lubricant in the temperature range of 89 to 227 K (160° to 410° R) in a five-ball fatigue tester (refs. 4 to 6) to conduct rolling-element fatigue tests. There was no statistically significant difference between the rolling-element fatigue lives obtained with a fluorinated ether at 169 K (305° R) with a viscosity of 10×10^{-6} square meter per second (10 cS) and that obtained with a super-refined naphthenic mineral oil at 328 K (590° R) with a viscosity of 37×10^{-6} square meter per second (37 cS). This result indicated that at lower temperatures with the fluorinated ether lubricant fluid, no derating of the fatigue life of AISI 52100 steel is necessary.

The research of reference 6 reported that elastohydrodynamic lubrication was obtained with fluorinated ether lubricants at outer-race temperatures from 89 to 228 K (160° to 410° R), even where outer-race temperatures were lower than the pour points of the fluids. The operating characteristics of the fluorinated ether fluids at cryogenic temperatures compared favorably with those of the super-refined mineral oil at room temperature.

Further research reported in reference 5, indicated that there was a slight decrease in fatigue life with increased contact angle. However, the differences in fatigue life were not statistically significant. The decrease in fatigue life with contact angle in the fluorinated ether fluid at 170 K (305° R) was identical to the trend with a diester fluid at 328 K (590° R). Analysis of the data of reference 5 indicate that the decrease in fatigue life was caused by decreased elastohydrodynamic film thickness and decreased ball hardness due to increased contact temperature at greater contact angles.

Lubricant viscosity can have a marked effect on rolling-element fatigue life through its effect on elastohydrodynamic film thickness. The effect of viscosity ν on life for a mineral oil was shown in references 9 and 10 to have the relation of $\text{Life} \propto \nu^m$. The exponent m can be taken as being 0.2. However, later research (ref. 11) would indicate that where there was nearly full separation of the surfaces by an elastohydrodynamic film, the effect of lubricant viscosity would be minimized. That is, little or no change in life would be anticipated by either increasing or decreasing the fluids viscosity.

The objective of the research reported herein was to determine the effect of the viscosity of fluorinated ether lubricants on rolling-element fatigue at cryogenic temperatures. In order to accomplish this objective rolling-element fatigue tests were conducted in the NASA five-ball fatigue tester with AISI 52100 steel 12.7-millimeter- (1/2-in.-) diameter balls in four different viscosity-level fluorinated ether lubricants. Test conditions included a bulk lubricant temperature of 200 K (360° R), a shaft speed of 4750 rpm, a maximum Hertz stress of 5500 meganewtons per square meter (800 000 psi), and a contact angle of 20°. The lubricant viscosities at test temperature ranged from 2.2×10^{-6} to 1600×10^{-6} square meter per second (2.2 to 1600 cS).

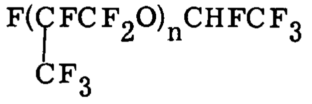
APPARATUS

The test apparatus used in these experiments is a modified NASA five-ball fatigue tester (see fig. 1(a)). The tester has an upper-test ball which is analogous to the inner race of an angular-contact bearing. The upper ball is pyramided on four equally spaced lower test balls that are positioned by a retainer and are free to rotate in an outer race (fig. 1(b)). The upper test ball is driven by, and axially loaded through, a drive shaft. The test block, which contains the outer race, is supported by support rods in rubber mounts to minimize stresses due to vibratory loads and minor misalinements. The test block includes an annular vacuum-jacketed liquid-nitrogen Dewar (fig. 1(a)). In this application, the liquid nitrogen acts as a heat sink with a temperature of 78 K (140° R) and does not contact the test assembly. The five-ball test assembly (fig. 1(b)) is completely submerged in the fluorinated ether test fluid which acts both as a heat-transfer medium and a lubricant.

The lower test block and Dewar, which are constructed of stainless steel, are covered with a layer of polystyrene foam to insulate them against undue heat leakage from the environment. The sources of heat within the test block region are the heat leak down the drive 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.

TEST LUBRICANTS

The test lubricants used in this research were a family of fluorinated ethers having the following general formula:



$$F(\underset{CF_3}{\underset{|}{C}}FCF_2O)_nCHFCF_3$$

where $n = 1, 2, 3,$ or 4.

Four fluids with different viscosities were used. These fluids are designated E-1, E-2, E-3, and E-4. The 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. Lubricant properties are summarized in table I. The kinematic viscosities and densities of the lubricants as functions of temperature are shown in figure 2.

SPECIMENS AND PROCEDURE

The test specimens were 12.7-millimeter- (1/2-in.-) diameter AISI 52100 steel balls with a nominal Rockwell C hardness of 61 at room temperature. The balls were thoroughly cleaned by immersion in a 95-percent ethyl alcohol solution. They were removed from the cleaning solution and air dried. The balls were inserted into the test assembly, and enough lubricant was added to entirely cover the five-ball assembly.

An axial load was applied to produce a maximum Hertz stress of 5500 meganewtons per square meter (800 000 psi) in the upper ball-lower ball contact. The Dewar was filled with liquid nitrogen and, when the outer-race temperature reached 228 K (410° R), the apparatus was started. The outer-race temperature was controlled by sensing and controlling the liquid nitrogen level with a thermocouple and a control system. The bulk lubricant temperature was maintained at 200 K (360° R) during testing with each of the four lubricants.

The shaft speed was maintained constant at 4750 rpm. An accelerometer-type vibration pickup was used to provide automatic shutdown of the apparatus when a fatigue spall occurred. A group of at least twenty-four tests was run with each of the four fluids. Lower-ball failures as well as upper-ball failures were used in the statistical analysis of the fatigue data.

RESULTS AND DISCUSSION

Fatigue Results

Rolling-element fatigue tests were run in the NASA five-ball fatigue tester with 12.7-millimeter- (1/2-in.-) diameter AISI 52100 steel balls. The tests were run at a maximum Hertz stress of 5500 meganewtons per square meter (800 000 psi), a shaft speed of 4750 rpm, a contact angle of 20°, and a bulk lubricant temperature of 200 K (360° R).

Four lubricants were used. They were from a family of fluorinated ethers and are referred to as E-1, E-2, E-3, and E-4. Using the test data of reference 4, the upper ball-lower ball contact temperature was determined to be 218 K (393° R) for a constant bulk lubricant temperature of 200 K (360° R). The viscosity of these four fluids at these temperatures are given in table II.

The results of the fatigue tests are shown in the Weibull plots of figure 3 and are summarized in table II.

In comparing several populations of statistical data, the statistical confidence in the reliability of the ranking of the populations, should be determined. Reference 12 provides a method of computing a confidence number. A confidence number of 95-percent means that 95 times out of 100 the population with that number will have the relative rank shown. A 68-percent confidence is approximately equal to a one sigma deviation, which, is considered to be statistically insufficient to conclude that there is any significant difference in life between two population groups.

Confidence numbers between the life with E-1 and those lives obtained using E-2, E-3, and E-4 were 50, 70, and 64 percent, respectively.

These numbers would indicate, that there are no statistically significant differences among the lives obtained with the four different viscosity-level lubricants.

Elastohydrodynamic Effects

A probable explanation for the lack of a viscosity-life relation for the data reported is the effect of elastohydrodynamic lubrication film thickness on rolling-element fatigue life. In figure 4 the measure of the effect of elastohydrodynamic film thickness on rolling-element fatigue life is presented (ref. 11). The effectiveness of the lubricant film is the lubricant film parameter Λ. (Symbols are defined in appendix A.)

$$\Lambda = \frac{h}{\sigma}$$

where

h	elastohydrodynamic film thickness, m (in.)
σ	composite surface roughness, $\sqrt{\sigma_1^2 + \sigma_2^2}$, m (in.) rms
σ_1, σ_2	surface roughness of mating elements, m (in.) rms

Lubricant film parameters Λ were calculated (see appendix B) for the test conditions at two assumed temperatures, 200 K (360° R) which is the bulk lubricant temperature and 218 K (393° R) which is the upper-ball temperature. The results of these calculations are summarized in table III. The values presented should only be considered as approximations inasmuch as the value of the pressure-viscosity exponent α for the fluorinated ether lubricants was assumed and not experimentally determined. However, these values of Λ would suggest, with the possible exception of the Λ values for fluid E-1, that the tests were run in an elastohydrodynamic regime ($\Lambda \geq 2$) where no effects on rolling-element fatigue would be expected (see fig. 4).

Based upon experience, the running tracks of the rolling-elements at Λ values of approximately 2 or greater should not appear significantly different considering, of course, small amounts of wear at startup and shutdown. In order to determine if differences in the running tracks did exist among the various fluids under the test conditions, surface profile traces were randomly made on upper-test balls which had been run for approximately 50 hours with each of the four designated fluids. Typical profile traces are shown in figure 5. From figure 5 it can be concluded that there exists a marked similarity in the running tracks of the ball specimens run with each of the four lubricants. The variation among the traces shown are no greater than the variation that may exist on a single ball track. This would be a strong indication that Λ values for the four lubricants were greater than 2.

SUMMARY OF RESULTS

Rolling-element fatigue tests were conducted in the NASA five-ball fatigue tester with AISI 52100 12.7-millimeter- (1/2-in.-) diameter steel balls in four different viscosity-level fluorinated ether lubricants. Test conditions included a bulk lubricant temperature of 200 K (360° R), a shaft speed of 4750 rpm, a maximum Hertz stress of 5500 meganewtons per square meter (800 000 psi), and a contact angle of 20°. The test viscosities ranged from 2.2×10^{-6} to 1600.0×10^{-6} square meter per second (2.2 to 1600 cS). The following results were obtained:

1. No statistically significant differences in rolling-element fatigue life occurred using the four viscosity levels.

2. Elastohydrodynamic calculations and the physical appearance of the specimen running tracks indicate that values of the lubricant film parameter Λ were approximately 2 or greater with the possible exception of that of the lowest viscosity level.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 17, 1975,
505-04.

APPENDIX A

SYMBOLS

C	constant in eq. (A2), K; $^{\circ}$R
E	modulus of elasticity, N/m^2; $lbf/in.^2$
E'	equivalent modulus of elasticity, $E/(1 - \nu^2)$, N/m^2; $lbf/in.^2$
h	calculated elastohydrodynamic film thickness, m; in.
k	constant in eq. (A11), $m^{2.48}/(N\text{-}sec)^{0.74}$; $in.^{2.48}/(lbf\text{-}sec)^{0.74}$
m	viscosity-life exponent
n	degree of polymerization in formula for fluorinated ethers
R	equivalent radius, $r/2$, m; in.
r	ball radius, m; in.
r_1, r_2	radius defined in fig. 1(b)
T_{LUB}	lubricant temperature, K; $^{\circ}$R
$T_{UPPER\ BALL}$	upper-ball temperature, K; $^{\circ}$R
U_1, U_2	velocity, m/sec; in./sec
u	equivalent velocity, m/sec; in./sec
W	ball normal load, N; lbf
α	pressure coefficient of viscosity, m^2/N; $in.^2/lbf$
β	contact angle, deg
Λ	lubricant film parameter, h/σ
μ_o	absolute viscosity at atmospheric pressure and lubricant temperature, $\rho\nu_o$, $N\text{-}sec/m^2$; $lbf\text{-}sec/in.^2$
ν	Poisson's ratio
ν_o	kinematic viscosity, m^2/sec; $in.^2/sec$
ρ	density, g/m^3; $lbm/in.^3$
σ	composite surface finish, $\sqrt{\sigma_1^2 + \sigma_2^2}$, m; in.
σ_1, σ_2	surface finishes of two surfaces in contact, m; in.
$\omega_1, \omega_2, \omega_3$	angular velocities defined in fig. 1(b)

APPENDIX B

CALCULATION OF ELASTOHYDRODYNAMIC FILM THICKNESS AND LUBRICANT FILM PARAMETER

From reference 13, the elastohydrodynamic film thickness h for point contact can be calculated from the following formula:

$$h = 1.4(\mu_o \alpha u)^{0.74} R^{0.407} \left(\frac{E'}{W}\right)^{0.074} \tag{B1}$$

where

E	modulus of elasticity, N/m^2; $lbf/in.^2$
E'	equivalent modulus of elasticity, $E/(1 - \nu^2)$, N/m^2; $lbf/in.^2$
R	equivalent radius, $r/2$, m; in.
r	ball radius, m; in.
u	equivalent velocity, m/sec; in./sec
W	ball normal load, N; lbf
α	pressure coefficient of viscosity, m^2/N; $in.^2/lbf$
μ_o	absolute viscosity at atmospheric pressure and lubricant temperature, $\rho\nu_o$, $(N)(sec)/m^2$; $(lbf)(sec)/in.^2$
ρ	density, g/m^3; $lbm/in.^3$
ν	Poisson's ratio
ν_o	kinematic viscosity, m^2/sec; $in.^2/sec$

From reference 4, the upper ball temperature may be determined. For a contact angle β of 20^o, the lubricant temperature $T_{LUB} = 200$ K (360^o R) and

$$T_{UPPER\ BALL} = T_{LUB} + C \tag{B2}$$

For $\beta = 20^o$, $C = 18$ K (33^o R). Therefore, $T_{UPPER\ BALL} = 218$ K (393^o R). The lubricant absolute viscosity is given by

$$\mu_o = \rho\nu_o \tag{B3}$$

It is assumed that the lubricant temperature in the upper ball-lower ball contact is equal to that of the upper ball, 218 K (393° R). The lubricant properties at a temperature of 218 K (393° R) are given in table IV.

Similarly, for an assumed bulk lubricant temperature of 200 K (360° R), the lubricant properties are given in table V.

In the five-ball tester (fig. 4), the surface speed of the upper ball U_1 at the upper ball-lower ball contact is

$$U_1 = \omega r_1 \tag{B4}$$

and

$$r_1 = r \cos \beta \tag{B5}$$

$$U_2 = \omega_c r_2 \tag{B6}$$

and

$$r_2 = 2r \cos \beta \tag{B7}$$

$$U_2 = \frac{U_1}{2} \tag{B8}$$

Substituting equations (B4) to (B7) into equation (B8) gives

$$\omega_c = \frac{\omega}{4} \tag{B9}$$

and

$$\omega_b = \frac{\omega}{2}$$

From reference 14, the equivalent velocity is

$$u = \frac{r_1}{2}\left[(\omega - \omega_c) + (\omega_b + \omega_c)\right]$$

$$= 0.75\ \omega r \cos \beta \tag{B10}$$

For an ω_1 of 4750 rpm (497 rad/sec),

$$u = 2.2 \text{ m/sec (88 in./sec)}$$

For 12.7-millimeter- (0.5-in.-) diameter balls, the equivalent radius is

$$R = \frac{r}{2} = 15.7\times10^{-3} \text{ m (0.125 in.)}$$

The equivalent modulus of elasticity is

$$E' = 219\ 000 \text{ MN/m}^2 \ (32\times10^6 \text{ lbf/in.}^2)$$

and the normal load is

$$W' = 761 \text{ N (171 lbf)}$$

The pressure-viscosity coefficient α is assumed to be 3.6×10^{-8} m^2/N (2.5×10^{-4} psi^{-1}).

Substituting the appropriate values in equation (B1) for the five-ball fatigue tester

$$h = k\mu_o^{0.74} \tag{B11}$$

For h in terms of meters, $k = 3.3\times10^{-6}$ $[\text{m}^{2.48}/(\text{N-sec})^{0.74}]$ and in terms of inches, $k = 8.8\times10^{-2}$ $[\text{in.}^{2.48}/(\text{lbf-sec})^{0.74}]$.

The values for the elastohydrodynamic film thickness h are given for the four lubricants at both 200 K (360° R) and 218 K (393° R) in table III.

The relation between surface finish and theoretical minimum film thickness is a dimensionless lubricant film parameter Λ where

$$\Lambda = \frac{h}{\sigma} \tag{B12}$$

and

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{B13}$$

where σ_1, σ_2 is the surface finish of contacting bodies, m (in.). For the five-ball fatigue tests, $\sigma = 35.9\times10^{-9}$ m (1.4×10^{-6} in.). The values of Λ for the four lubricants are given along with the elastohydrodynamic film thicknesses in table III.

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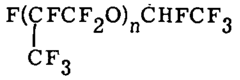
TABLE I. - PROPERTIES OF FLUORINATED POLYETHER LUBRICANTS[a]

General formula for family of fluorinated polyethers:  $F(\underset{CF_3}{\underset{\mid}{C}}FCF_2O)_nCHFCF_3$	Lubricant designation			
	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:				
K	312	374	426	466
($^{\circ}$R)	(562)	(673)	(767)	(839)
Compressibility at 298 K (537° R) and 500 atm, percent	8.20	6.48	5.64	5.18
Heat of vaporization at boiling point:				
cal/g	[b]23.0	[b]17.4	[b]14.5	[b]12.5
(Btu/lb)	(41.4)	(31.3)	(26.1)	(22.5)
Approximate pour point (0.2 m^2/sec; 200 000 cS):				
K	119	150	166	179
($^{\circ}$R)	(214)	(270)	(300)	(322)
Density at 298 K (537° R)				
g/cu cm	1.538	1.658	1.723	1.763
(lb/gal)	(13.2)	(13.8)	(14.3)	(14.7)
Specific heat, C_p:				
J/(kg)(K)	[b]1025	1025	1025	[b]1025
(Btu/(lb)($^{\circ}$R))	(0.245)	(0.244)	(0.243)	(0.241)
Thermal conductivity:				
J/(m)(sec)(K)	[b]311	[b]311	[b]311	[b]311
(Btu/(hr)(ft)($^{\circ}$R))	(0.05)	(0.05)	(0.05)	(0.05)
Thermal expansion:				
m^3/(kg)(K)	1.07×10^{-6}	0.91×10^{-6}	0.7×10^{-6}	0.64×10^{-6}
(ft^3/(lb)($^{\circ}$R))	(10×10^{-6})	(8.5×10^{-6})	(6.5×10^{-6})	(6×10^{-6})
Vapor pressure at 325 K (585° R)				
N/m^2 abs	163×10^{3}	14×10^{3}	1.6×10^{3}	0.56×10^{3}
(psia)	(23.7)	(2.03)	(0.23)	(0.082)
Viscosity at 298 K (537° R)				
m^2/sec	0.3×10^{-6}	0.6×10^{-6}	1.3×10^{-6}	2.3×10^{-6}
(cS)	(0.3)	(0.6)	(1.3)	(2.3)

[a] From ref. 7.

[b] Estimated values.

TABLE II. - ROLLING-ELEMENT FATIGUE LIFE ON AISI 52100 STEEL BALLS WITH FOUR FLUORINATED ETHER LUBRICANTS IN FIVE-BALL FATIGUE TESTER

[Maximum Hertz stress, 5500 MN/m^2 (800 000 psi); bulk lubricant temperature, 200 K (360° R); shaft speed, 4750 rpm; contact angle, 20°.]

Lubricant designation	Lubricant viscosity, cS		Fatigue life, stress cycles		Failure index[a]	Weibull slope
	At bulk lubricant temperature of 200 K (360° R)	At temperature of upper ball of 218 K (393° R)	Ten percent life	Fifty percent life		
E-1	2.2	1.3	7.4×10^{6}	34.6×10^{6}	25 out of 25	1.2
E-2	15.4	5.2	7.5	24.7	38 out of 42	1.6
E-3	150	26	4.6	20.1	46 out of 48	1.3
E-4	1600	150	6.0	25.6	57 out of 67	1.3

[a] Failure index indicates number of failures out of those tested.

TABLE III. - CALCULATED VALUES OF ELASTOHYDRODYNAMIC FILM THICKNESS AND LUBRICANT FILM PARAMETER FOR FLUORINATED ETHER LUBRICANTS IN FIVE-BALL FATIGUE TESTER

[Maximum Hertz stress, 5500 MN/m^2 (800 000 psi); speed, 4750 rpm.]

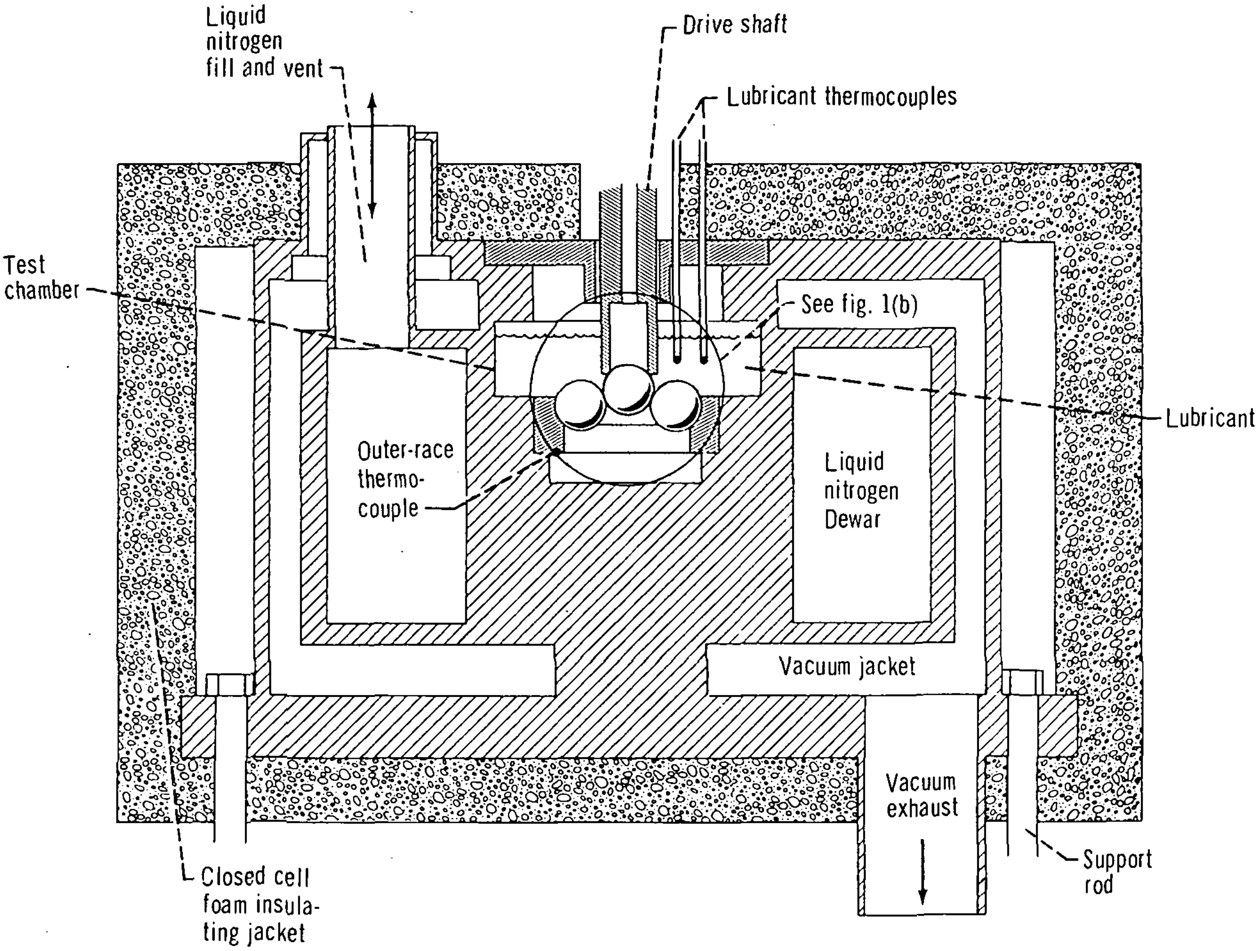
Lubricant designation	Lubricant temperature, K ($^{\circ}$R)					
	200 (360)			218 (393)		
	Elastohydrodynamic film thickness, h		Lubricant film parameter, Λ	Elastohydrodynamic film thickness, h		Lubricant film parameter, Λ
	m	in.		m	in.	
E-1	0.05×10^{6}	2.1×10^{6}	1.5	0.04×10^{6}	1.4×10^{6}	1
E-2	.24	9.4	6.7	.11	4.2	3
E-3	1.3	51	36	.36	14	10
E-4	7.6	298	213	1.4	56	14

TABLE IV. - LUBRICANT PROPERTIES AT 218 K (393° R)

Lubricant designation	Kinematic viscosity, ν_o		Density, ρ		Absolute viscosity, μ_o	
	m^3/sec	in.^{2}/sec	g/m^3	lbm/in.^{3}	N-sec/m^2	lbf-sec/in.^{2}
E-1	1.3×10^{-6}	2×10^{-3}	1.77×10^{6}	0.064	2.25×10^{-3}	0.326×10^{-6}
E-2	5.2	8.1	1.86	.067	9.67	1.40
E-3	26	40	1.91	.069	49.7	7.20
E-4	170	264	1.94	.070	3301	47.8

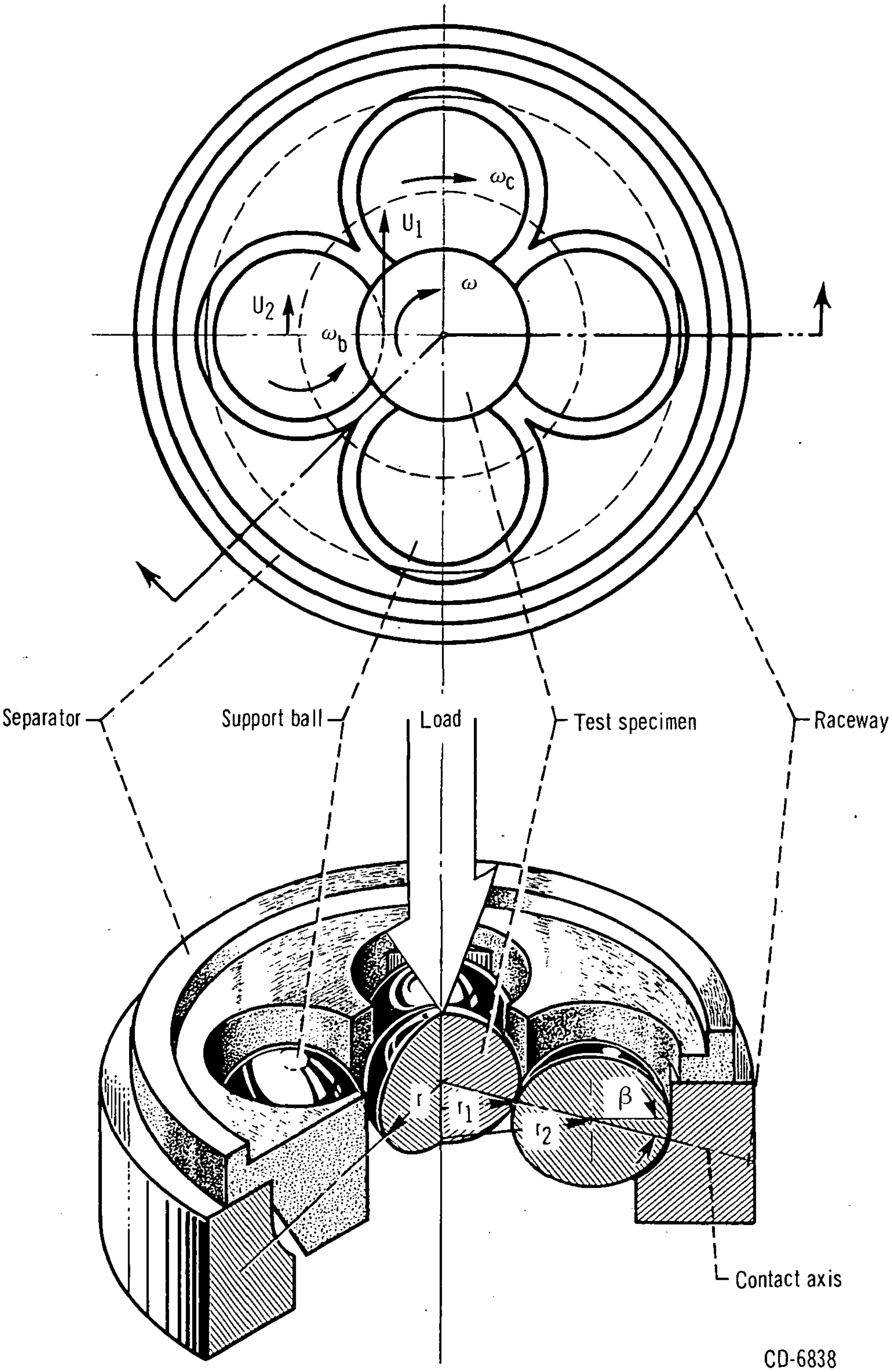
TABLE V. - LUBRICANT PROPERTIES AT 200 K (360° R)

Lubricant designation	Kinematic viscosity, ν_o		Density, ρ		Absolute viscosity, μ_o	
	m^2/sec	in.^{2}/sec	g/m^3	lbm/in.^{3}	N-sec/m^2	lbf-sec/in.^{2}
E-1	2.2×10^{-6}	3.4×10^{-3}	1.84×10^{6}	0.066	4.05×10^{-3}	0.587×10^{-6}
E-2	15.4	23.8	1.90	.069	29.2	4.24
E-3	150	233	1.95	.070	29.2	42.4
E-4	1600	2480	1.98	.072	3166	459



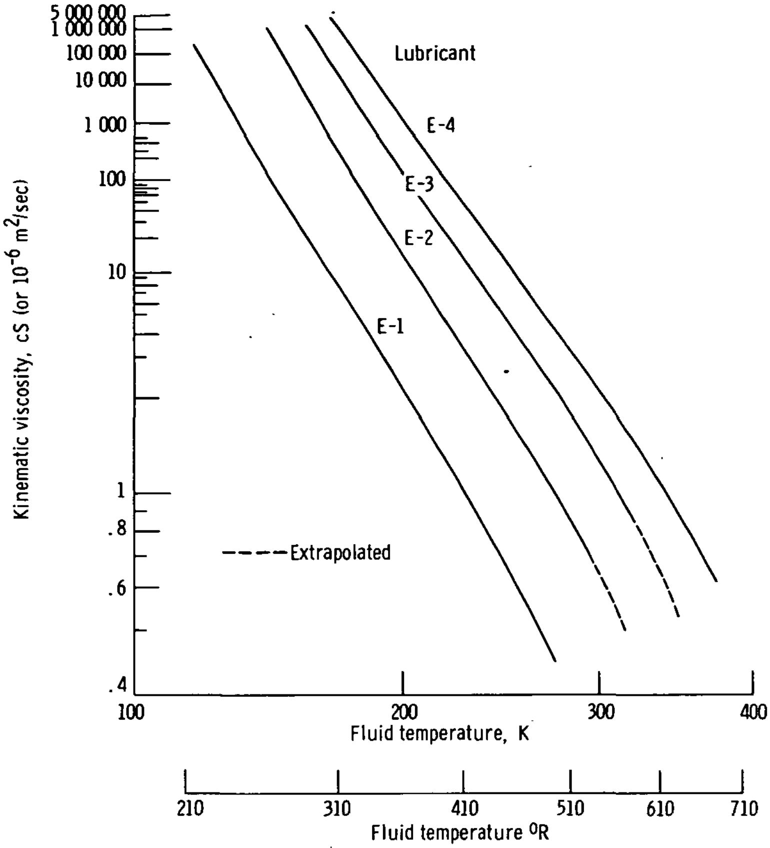
(a) Simplified cross section of test block.

Figure 1. - Cryogenic five-ball fatigue tester.

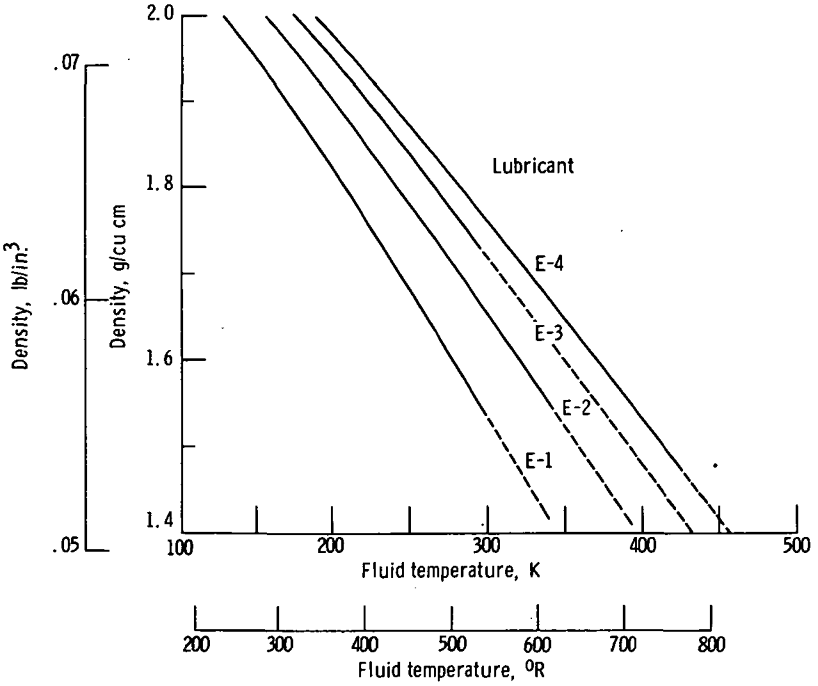


(b) Geometry and velocity relations in five-ball assembly.

Figure 1. - Concluded.

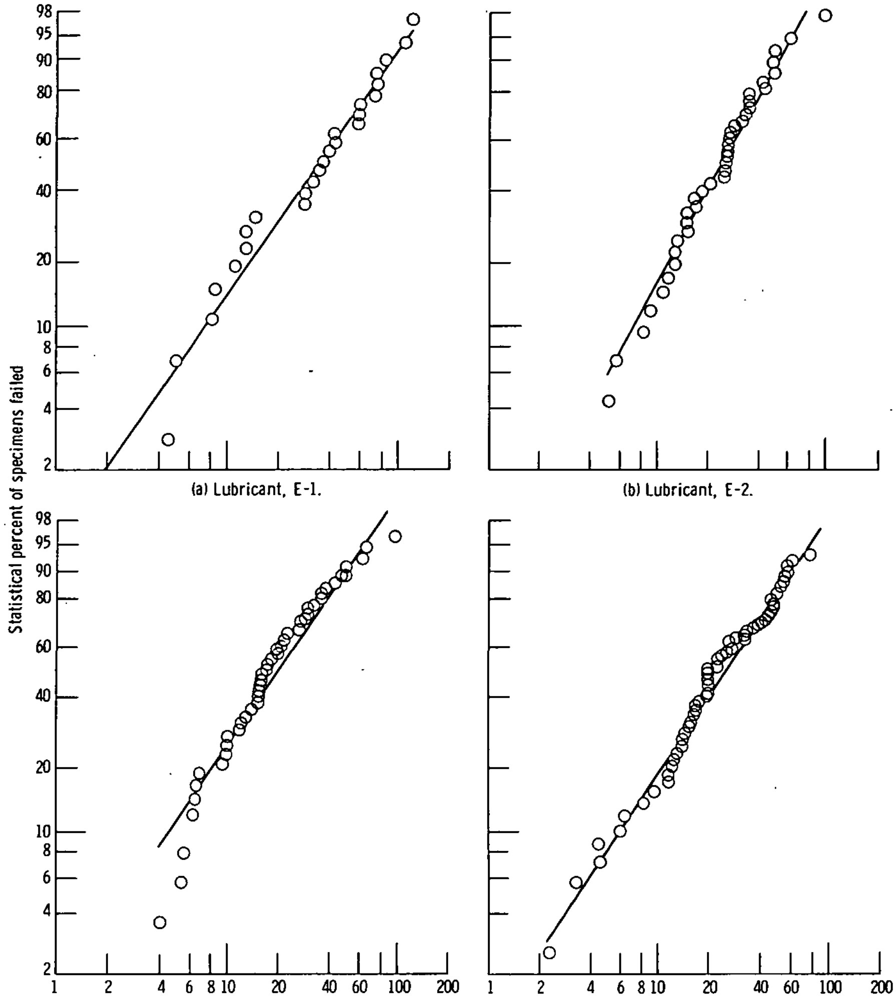


(a) Viscosity temperature relation.



(b) Density temperature relation.

Figure 2. - Lubricant properties of fluorinated ether lubricants (ref. 6).

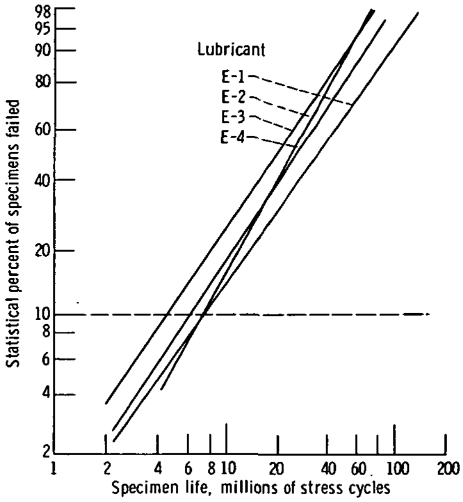


(a) Lubricant, E-1.

(b) Lubricant, E-2.

(c) Lubricant, E-3.

(d) Lubricant, E-4.



(e) Summary.

Figure 3. - Rolling-element fatigue life of AISI 52100 steel balls with four grades of fluorinated ether lubricant in five-ball fatigue tester. Maximum Hertz stress, 5500 MN/m^2 (800 000 psi); bulk lubricant temperature, 200 K (360° R); shaft speed, 4750 rpm; contact angle, 20°.

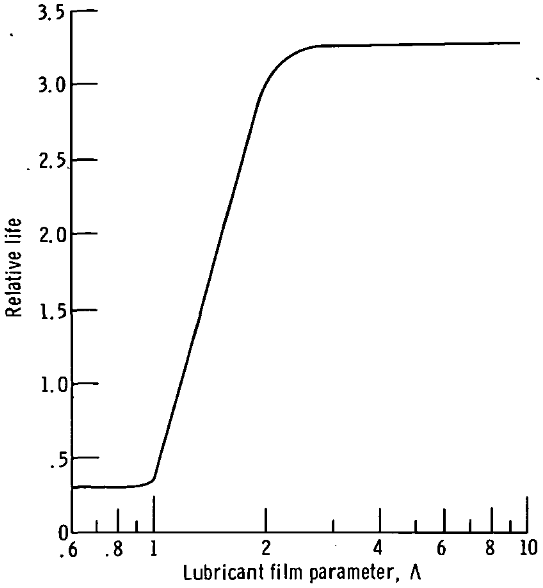
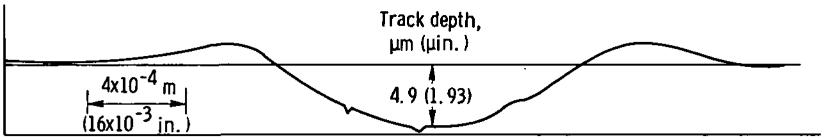
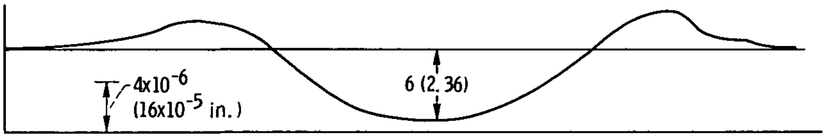


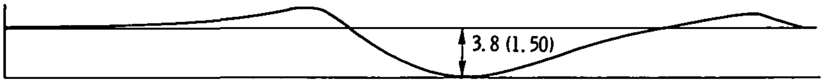
Figure 4. - Rolling-element fatigue life as a function of lubricant film parameter Λ (ref. 11).



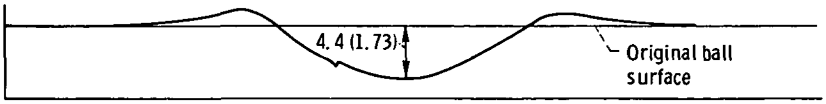
(a) Lubricant, E-1; viscosity at bulk lubricant temperature, 2.2×10^{-6} square meter per second (2.2 cS).



(b) Lubricant, E-2; viscosity at bulk lubricant temperature, 15.4×10^{-6} square meter per second (15.4 cS).



(c) Lubricant, E-3; viscosity at bulk lubricant temperature, 150.0×10^{-6} square meter per second (150.0 cS).



(d) Lubricant, E-4; viscosity at bulk lubricant temperature, 1600.0×10^{-6} square meter per second (1600.0 cS).

Figure 5. - Profile traces of typical upper ball running tracks. Maximum Hertz stress, 5500 MN/m^2 (800 000 psi); shaft speed, 4750 rpm; bulk lubricant temperature, 200 K (360^0 R); contact angle, 20^0; approximate running time, 50 hours (43x10^6 stress cycles).

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