NASA TECHNICAL NOTE

NASA TN D-5566

NASA TN D-5566



# ROLLING-ELEMENT LUBRICATION WITH FLUORINATED POLYETHER AT CRYOGENIC TEMPERATURES (160° TO 410° R)

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1969

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|---|---|---|
| 1. Report No. NASA TN D-5566 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle ROLLING-ELEMENT LUBRICATION WITH FLUORINATED POLYETHER AT CRYOGENIC TEMPERATURES ($160^{\circ}$ TO $410^{\circ}$ R) | | 5. Report Date November 1969 |
| | | 6. Performing Organization Code |
| 7. Author(s) Marshall W. Dietrich, Dennis P. Townsend, and Erwin V. Zaretsky | | 8. Performing Organization Report No. E-5018 |
| 9. Performing Organization Name and Address<br>Lewis Research Center<br>National Aeronautics and Space Administration<br>Cleveland, Ohio 44135 | | 10. Work Unit No. 126-15 |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, D.C. 20546 | | 13. Type of Report and Period Covered<br>Technical Note |
| | | 14. Sponsoring Agency Code |
| 15. Supplementary Notes | | |

16. Abstract

Rolling-element lubrication tests were conducted at temperatures from $160^{\circ}$ to $410^{\circ}$ R (89 to 227 K) in a modified NASA five-ball fatigue tester with SAE 52100 steel balls. Fluorinated polyether fluids of four different viscosity levels were used as the lubricant. Test results indicated that these fluids have the ability to form elastohydrodynamic films at cryogenic temperatures. At outer-race temperatures below the fluid pour points, these fluids had the ability to provide sufficient lubrication in this system. A linear correlation was developed between upper-ball (inner-race) temperature and measured lubricant temperature. Upper-ball (inner-race) temperature increased with increasing stress at the same rate for all four viscosity levels.

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| 17. Key Words *(Suggested by Author(s))*<br>Rolling element<br>Liquid lubricant<br>Lubrication<br>Cryogenic<br>Elastohydrodynamic lubrication | | 18. Distribution Statement<br>Unclassified - unlimited | |
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages<br>16 | 22. Price*<br>$3.00 |

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

# ROLLING-ELEMENT LUBRICATION WITH FLUORINATED POLYETHER AT CRYOGENIC TEMPERATURES (160° TO 410° R)

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## SUMMARY

Rolling-element lubrication tests were conducted with 1/2-inch-diameter (12.7-mm-) SAE 52100 steel balls. The tests were run in an NASA five-ball fatigue tester modified for cryogenic temperature testing. Test conditions included a drive shaft speed of 4750 rpm, a maximum Hertz stress range of 500 000 to 800 000 psi ($3.4\times10^9$ to $5.5\times10^9$ N/m$^2$), outer-race temperatures of $160^\circ$ to $410^\circ$ R (89 to 227 K), and contact angles of $10^\circ$, $20^\circ$, $30^\circ$, and $40^\circ$. Four fluorinated polyether fluids with different viscosities were used as the lubricants.

The deformation and wear of the test specimens lubricated with the fluorinated polyether fluids compared favorably with those of test specimens run at room temperature with conventional lubricants. This result indicates that the fluorinated polyether fluids have the ability to form adequate elastohydrodynamic films at outer-race temperatures from $160^\circ$ to $410^\circ$ R (89 to 227 K).

Adequate lubrication was obtained at outer-race temperatures below the fluid pour point with each of the four lubricants. At outer-race temperatures below each pour point, the upper-ball temperature and the lubricant temperature remained constant. At outer-race temperatures above the pour point of the lubricant, both upper-ball (inner-race) and lubricant temperatures increased at a constant rate with increasing outer-race temperature. In addition, the upper-ball temperature increased with increasing stress at the same rate for the four lubricants tested. The rate of temperature increase is approximately the same as that of a super-refined mineral oil at room temperature.

## INTRODUCTION

The need for reliable bearings in cryogenic systems has increased greatly in the last decade. These systems include the short-duration runs (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 (refs. 1 to 4).

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 (refs. 5 to 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 (refs. 5 to 7), 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 is the use of liquid lubricants. With a liquid lubricant, not only could a higher strength metal cage be used but also elastohydrodynamic lubrication would be provided in the rolling-element race contact. Wear of the balls, races, and retainer would be minimized. It is, therefore, probable that bearings could have much longer lives at cryogenic temperature than are 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 that exhibits many of the properties required for cryogenic applications is the fluorinated polyethers (refs. 8 and 9). While some of the fluid properties such as viscosity and heat-transfer characteristics are clearly defined, the ability of the fluids to provide adequate lubrication needs to be determined experimentally.

The research reported herein was undertaken to evaluate the performance of four fluorinated polyether fluids in a modified five-ball fatigue tester. The objectives were to (1) compare the lubricating characteristics of fluorinated polyether fluids at outer-race temperatures of $160^{\circ}$ to $410^{\circ}$ R (89 to 227 K) with those of a mineral oil at room temperature and (2) determine the effect of fluid viscosity, maximum Hertz stress, and contact angle on the system temperature.

These objectives were accomplished by conducting rolling-element lubrication tests in a modified five-ball fatigue tester. The specimens tested were 1/2-inch- (12.7-mm-) diameter SAE 52100 steel balls with a Rockwell C hardness of approximately 61 at room temperature. Test conditions included a drive shaft speed of 4750 rpm, a maximum Hertz stress range of 500 000 to 800 000 psi ($3.4\times10^{9}$ to $5.5\times10^{9}$ N/m$^{2}$), outer-race temperatures of $160^{\circ}$ to $410^{\circ}$ R (89 to 227 K), and contact angles of $10^{\circ}$, $20^{\circ}$, $30^{\circ}$, and $40^{\circ}$. Four fluorinated polyethers were used as the lubricants. Temperatures in the system were measured and analyzed. Lubrication effectiveness was analyzed with respect to wear and deformation of the ball running track and compared with that obtained with a super-refined mineral oil at room temperature. All experimental results for a given lubricant were obtained from the same lubricant batch. All ball specimens were from the same heat of material.

## APPARATUS

The test apparatus used in these experiments is a modifed NASA five-ball fatigue tester (see fig. 1(a)). The tester comprises an upper-test ball that 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 lower test block, which contains the outer race, is supported by 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 an infinite heat sink with a temperature of $140^{\circ}$ R (78 K). The five-ball test assembly (fig. 1(b)) is completely submerged in the lubricant. The fluid 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 to insulate it 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.

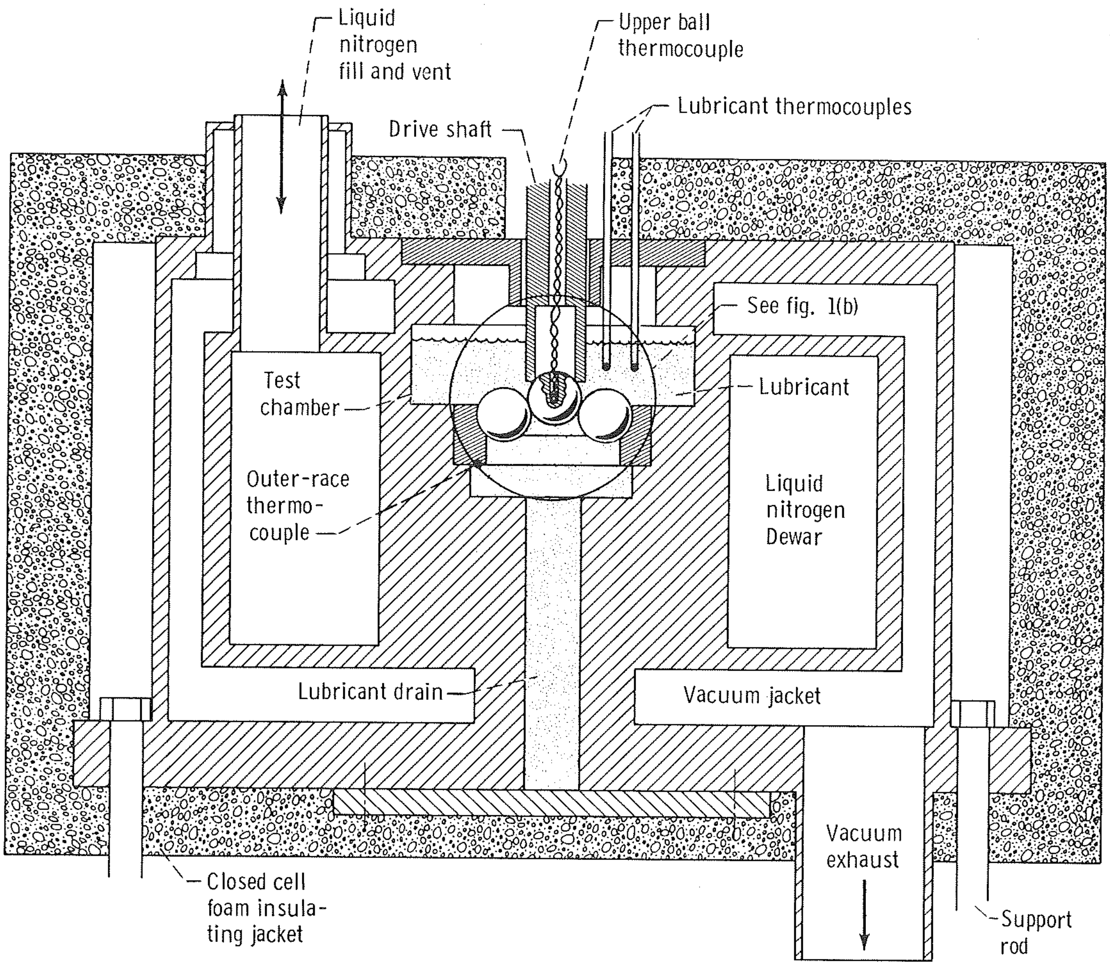
## TEST LUBRICANT

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

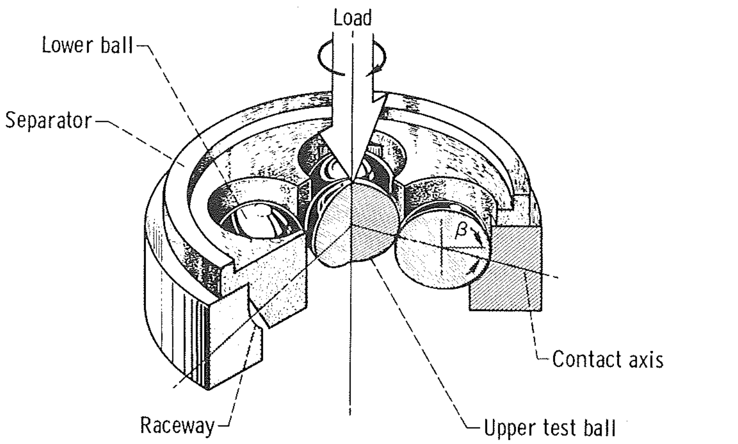
$$F(\underset{\substack{|\\ CF_3}}{C}FCF_2O)_nCHFCF_3$$

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

Four fluids with different viscosities were evaluated. 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




(a) Simplified cross section of low-temperature five-ball fatigue tester.




(b) Five-ball tester assembly.

Figure 1. - Test apparatus.

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

| General formula for family of fluorinated polyethers: $F(CF(CF_3)CF_2O)_nCHFCF_3$ | 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: | | | | |
| $^{o}R$ | 562 | 673 | 767 | 839 |
| (K) | (312) | (374) | (426) | (466) |
| Compressibility at 537$^{o}$ R (298 K) 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 |
| (cal/g) | (23.0) | (17.4) | (14.5) | (12.5) |
| Approximate pour point (200 000 cs; 0.2 $m^2$/sec): | | | | |
| $^{o}R$ | 214 | 270 | 300 | 322 |
| (K) | (118.6) | (149.7) | (166.3) | (178.6) |
| Density: | | | | |
| lb/gal | 13.2 | 13.8 | 14.3 | 14.7 |
| (g/cc) | (1.538) | (1.658) | (1.723) | (1.763) |
| Specific heat, $C_p$: | | | | |
| Btu/(lb)($^{o}$R) | [b]0.245 | 0.244 | 0.243 | [b]0.241 |
| (J/(kg)(K)) | (1025) | (1025) | (1025) | (1025) |
| Thermal conductivity: | | | | |
| Btu/(hr)(ft)($^{o}$R) | [b]0.05 | [b]0.05 | [b]0.05 | [b]0.05 |
| (J/(m)(sec)(K)) | (311) | (311) | (311) | (311) |
| Thermal expansion: | | | | |
| $ft^3$/(lb)($^{o}$R) | $10\times10^{-6}$ | $8.5\times10^{-6}$ | $6.5\times10^{-6}$ | $6\times10^{-6}$ |
| ($m^3$/(kg)(K)) | ($1.07\times10^{-6}$) | ($0.91\times10^{-6}$) | ($0.7\times10^{-6}$) | ($0.64\times10^{-6}$) |
| Vapor pressure at 585$^{o}$ R (325 K): | | | | |
| psia | 23.7 | 2.03 | 0.23 | 0.082 |
| (N/$m^2$ abs) | ($163\times10^3$) | ($14\times10^3$) | ($1.6\times10^3$) | ($0.56\times10^3$) |
| Viscosity at 537$^{o}$ R (298 K): | | | | |
| cs | 0.3 | 0.6 | 1.3 | 2.3 |
| ($m^2$/sec) | ($0.3\times10^{-6}$) | ($0.6\times10^{-6}$) | ($1.3\times10^{-6}$) | ($2.3\times10^{-6}$) |

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

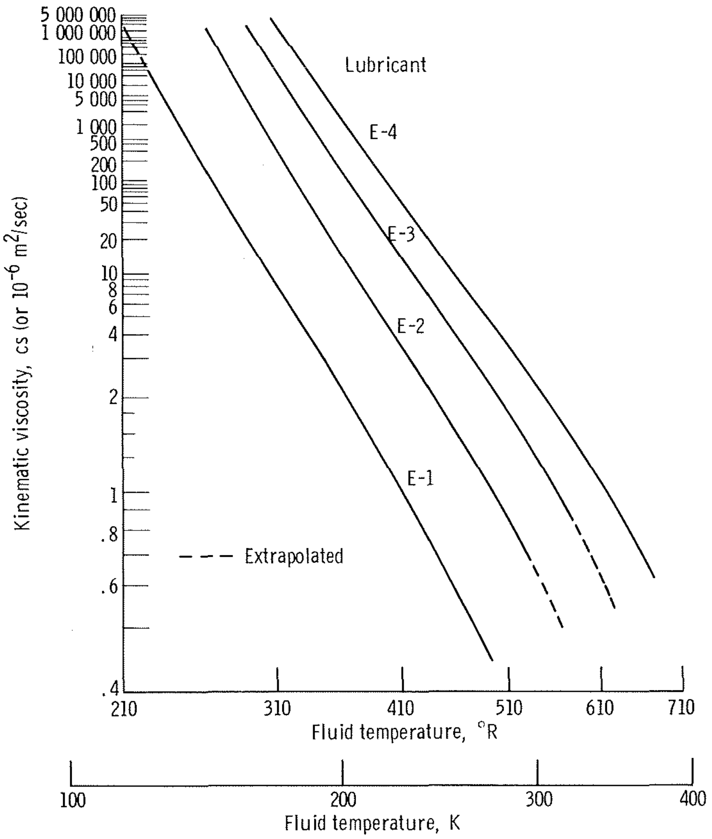



Figure 2. - Temperature-viscosity relation for test lubricants (ref. 8).

degree of polymerization increases. Lubricant properties are summarized in table I. The viscosities of the lubricants as functions of temperature are shown in figure 2.

## SPECIMENS AND PROCEDURE

The test specimens were 1/2-inch- (12.7-mm-) 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-percent 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 cover entirely the five-ball assembly. An axial load was applied to the five-ball system. Liquid nitrogen was added to the Dewar to cool the system to the operating temperature. As the outer-race temperature reached 385° R (214 K), the drive motor was started, and 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 sets of temperature readings showed no change). The average test duration was about 2 hours.

The lubricant temperature was measured at two different stations in the test cavity at radial distances approximately 1/4 inch (6.4 mm) apart (see fig. 1(a)). The upper-ball temperature was measured during operation by means of a thermocouple inserted in the center of the ball. The thermocouple emf was obtained through a slipring-brush assembly.

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 a superrefined mineral oil at room temperature.

## RESULTS AND DISCUSSION

Rolling-element lubrication tests were conducted with 1/2-inch- (12.7-mm-) diameter SAE 52100 steel balls in an NASA five-ball fatigue tester modified for low-temperature operation. Four fluorinated polyether fluids with different viscosities were used as the lubricants. Test conditions included outer-race temperatures of $160^{\circ}$ to $410^{\circ}$ R (89 to 227 K), a drive shaft speed of 4750 rpm, and maximum Hertz stresses of 500 000 to 800 000 psi ($3.4\times10^{9}$ to $5.5\times10^{9}$ N/m$^2$).

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 $260^{\circ}$ R (144 K) and the four lubricants tested. These data show that, at a constant outer-race temperature, the upper-ball temperature increases slightly as contact angle (ball spin velocity) increases. This result is not unexpected since increased ball spin velocity generates more frictional heat in the contact zone, thereby raising the temperature. These

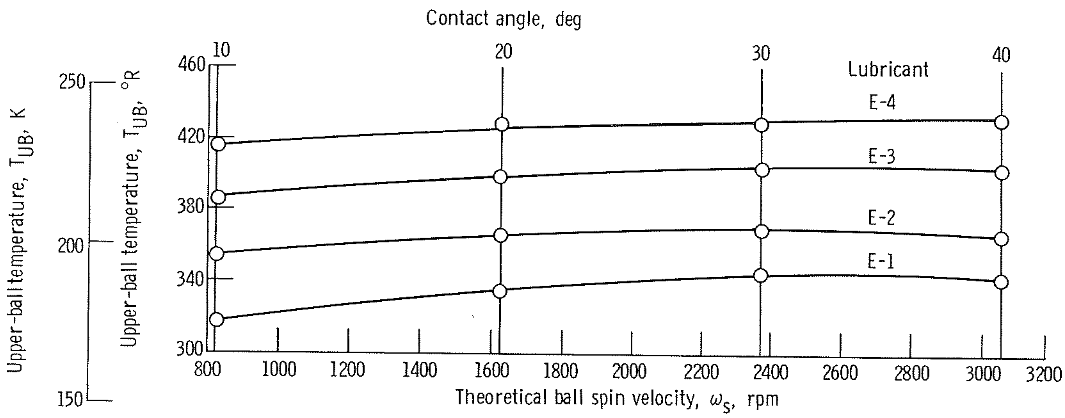



Figure 3. - Upper-ball temperature as function of theoretical ball spin velocity for constant outer-race temperature of 260° R (144.4 K); maximum Hertz stress, 800 000 psi ($5.5\times10^{9}$ N/m$^2$); shaft speed, 4750 rpm.

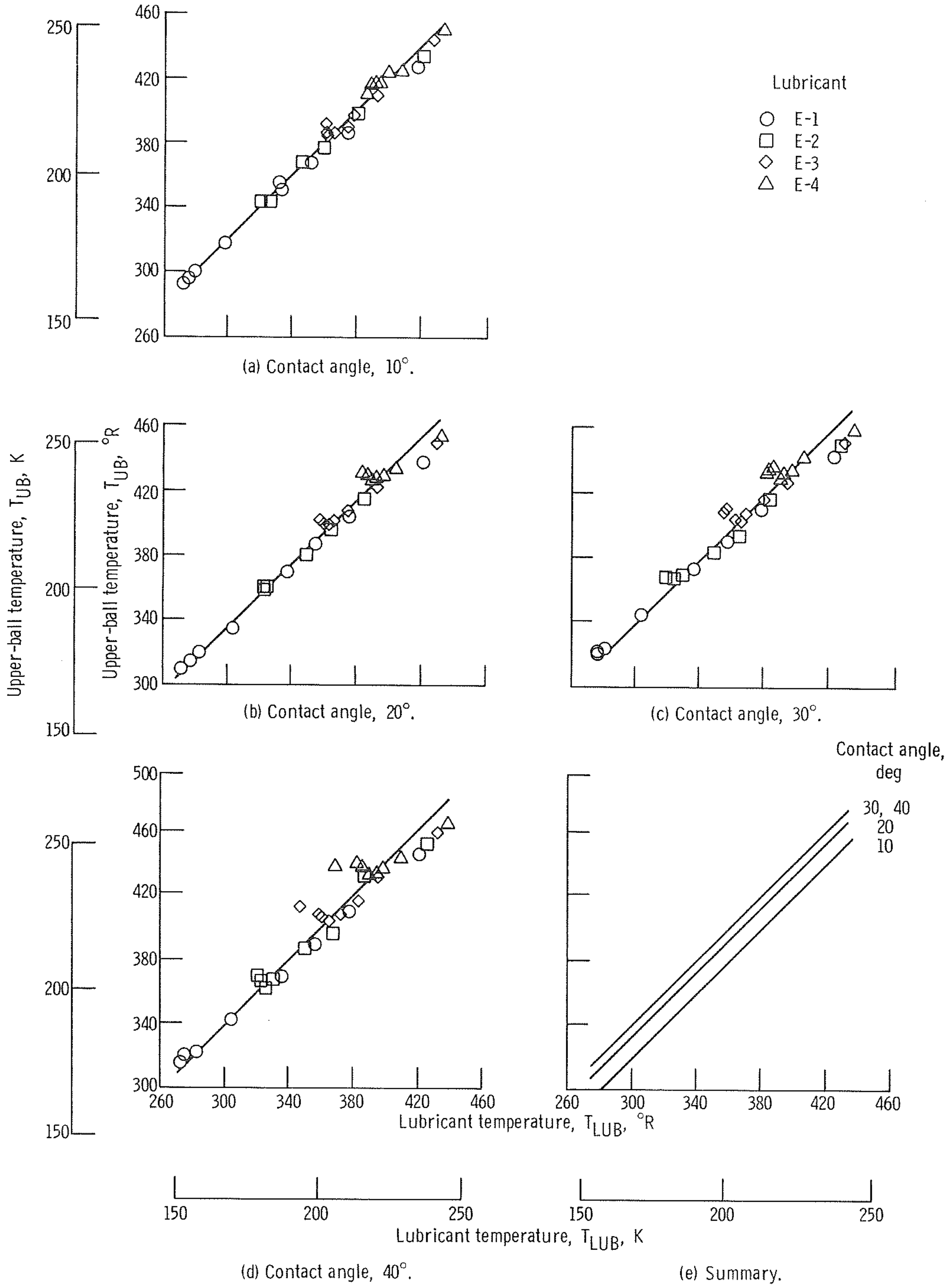



Figure 4. - Upper-ball temperature as function of lubricant temperature. Maximum Hertz stress, 800 000 psi ($5.5 \times 10^9$ N/m$^2$); shaft speed, 4750 rpm.

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

A plot of the upper-ball temperature as a function of the lubricant temperature is shown in figure 4 for the four fluids at the four contact angles. 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 $^{o}R$ (K)) can be written as

$$T_{upper\,ball} = T_{lub} + C$$

where

$C = 19^{o}$ R (10.5 K) for $10^{o}$ contact angle

$C = 33^{o}$ R (18 K) for $20^{o}$ contact angle

$C = 40^{o}$ R (22 K) for $30^{o}$ contact angle

$C = 40^{o}$ R (22 K) for $40^{o}$ 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. For each of the lubricants, there is an outer-race temperature range wherein both the lubricant and the upper-ball temperatures remain relatively constant as the outer-race temperature increases. This range is coincident with the 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 best be 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 upper ball begin to increase as the outer-race temperature increases.

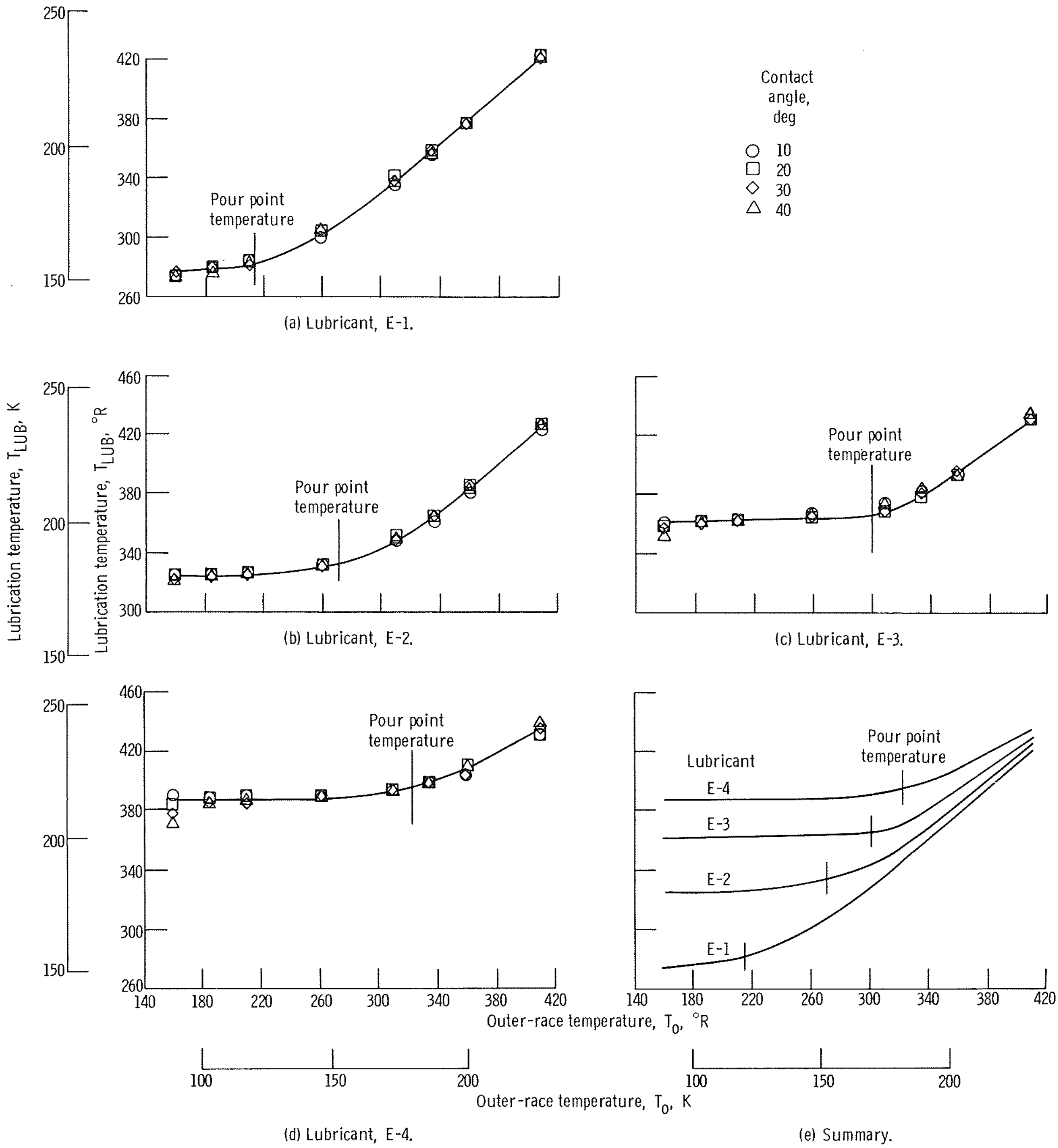



Figure 5. - Lubricant temperature as function of outer-race temperature. Maximum Hertz stress, 800 000 psi ($5.5\times10^{9}$ N/m$^2$); shaft speed, 4750 rpm.

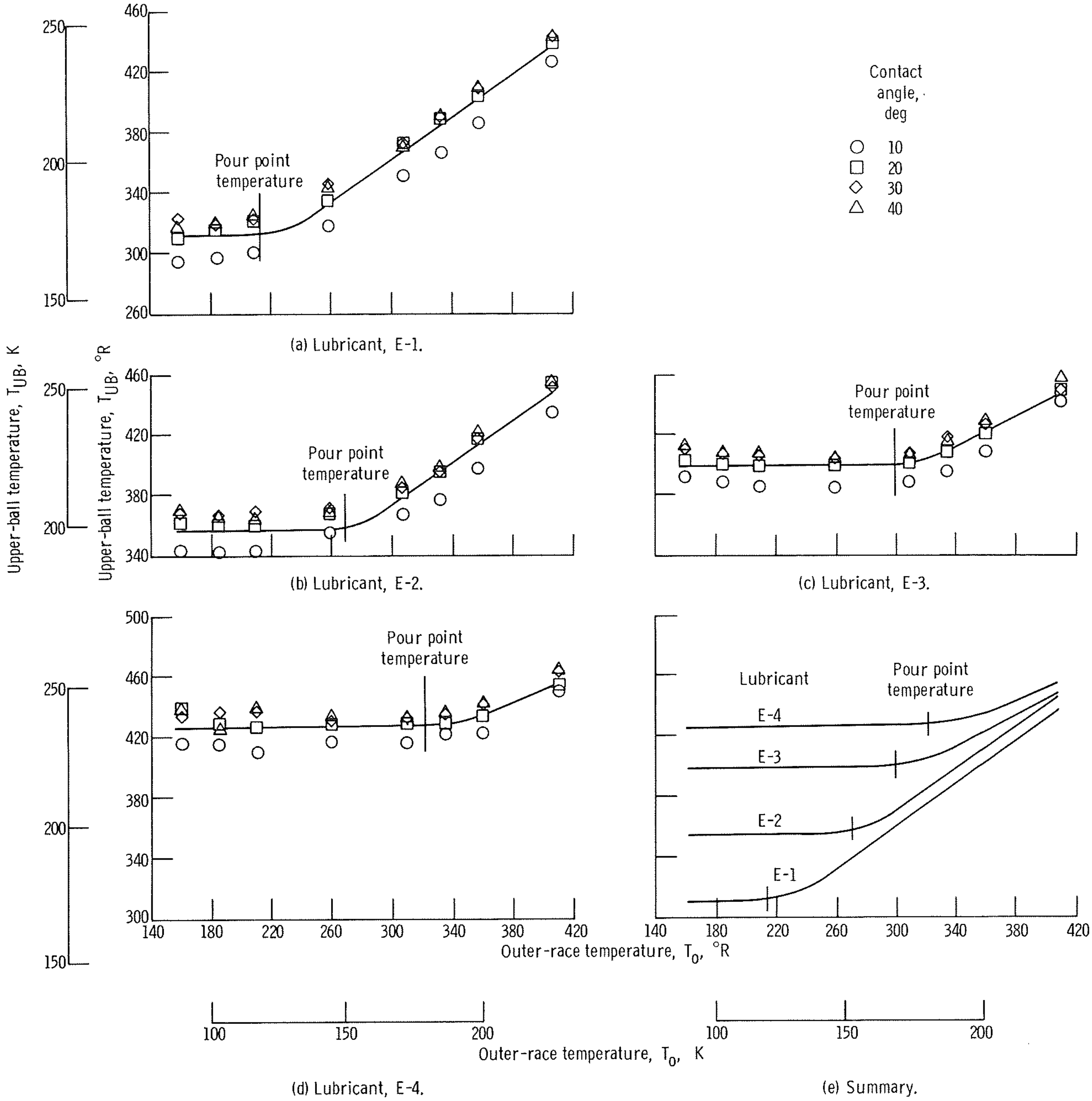



Figure 6. - Upper-ball temperature as function of outer-race temperature. Maximum Hertz stress, 800 000 psi ($5.5\times10^9$ $N/m^2$); shaft speed, 4750 rpm.

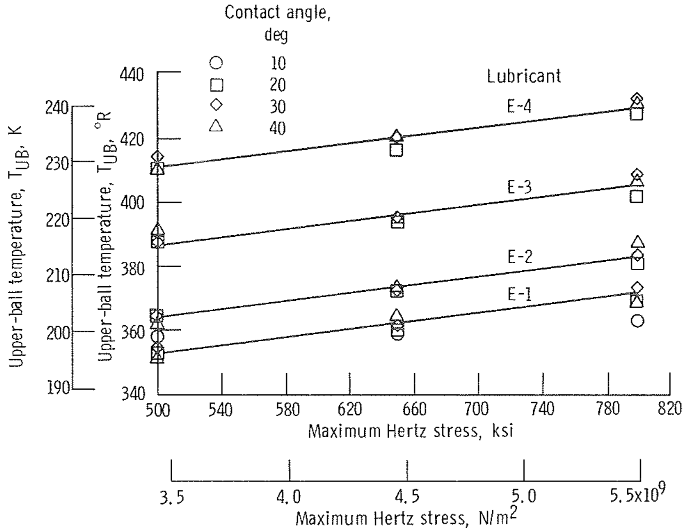



Figure 7. - Upper-ball temperature as function of maximum Hertz stress for constant outer-race temperature of 310° R (172 K); shaft speed, 4750 rpm.

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 lubricants tested, the upper-ball temperature increased with increasing maximum Hertz stress. The rate of increase for these data is approximately $5^{\circ}$ R (2.8 K) per 100 000 psi ($6.89\times10^{8}$ $N/m^2$) maximum Hertz stress in the range between 500 000 and 800 000 psi ($3.4\times10^{4}$ and $5.5\times10^{9}$ $N/m^2$). Comparative data for a conventional lubricant at room temperature are shown in figure 8, where the rate of temperature increase is seen to be approximately the same as that with the conventional lubricant. 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 fluid at $340^{\circ}$ R (189 K) is compared with that of a representative specimen lubricated with a super-refined mineral oil at room temperature. This mineral oil is known to provide elastohydrodynamic lubrication under the conditions indicated.

Rolling contact under these conditions (fig. 9) results in an alteration of the rolling-element surfaces. This effect manifests itself in three basic forms: (1) elastic deformation, (2) plastic deformation, and (3) 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 (fig. 9(b)) shows that the permanent deformation was approximately the same as that obtained with the mineral oil (fig. 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 $160^{\circ}$ to $410^{\circ}$ R (89 to 227 K) are comparable with a mineral oil lubricant at moderate temperatures, $560^{\circ}$ to $760^{\circ}$ R (311 to 478 K). Thus, it can be concluded that the fluorinated

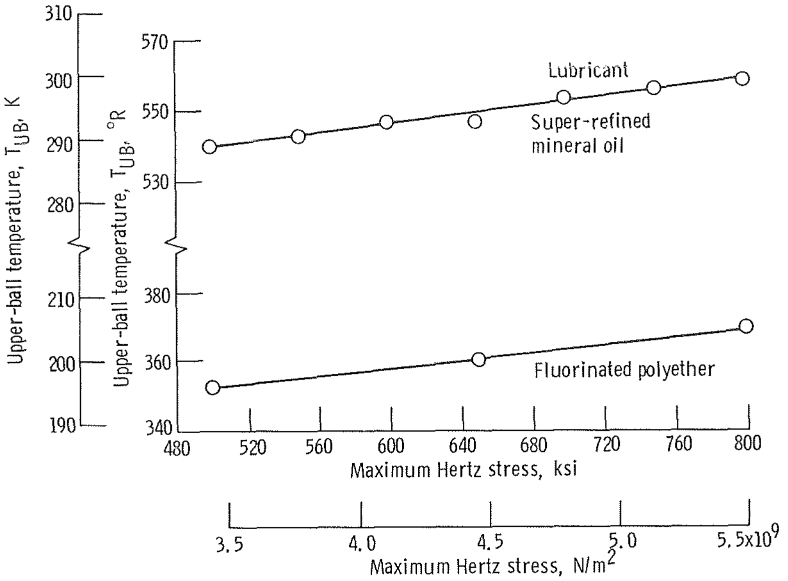
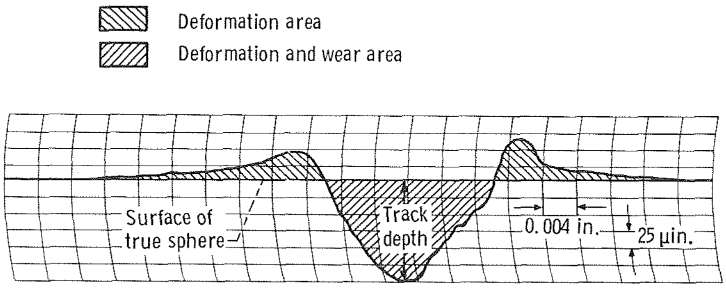
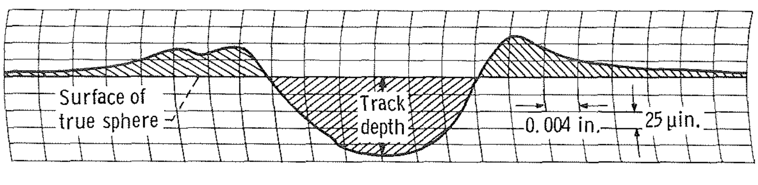



Figure 8. - Upper-ball temperature as function of maximum Hertz stress. Shaft speed, 4750 rpm; outer-race temperature, 310° and 510° R (172 and 283 K) for fluorinated polyether and super-refined mineral oil, respectively; contact angle, 20°.




(a) Lubricant, super-refined mineral oil; shaft speed, 4900 rpm; running time, 22 hours; ball-temperature, approximately 590° R (328 K).




(b) Lubricant fluorinated polyether; shaft speed, 4750 rpm; running time, 19 hours; ball temperature, 340° R (189 K).

Figure 9. - Magnified running track profiles of 1/2-inch- (12.7-mm-) diameter SAE 52100 steel upper-test ball specimens. Contact angle, 20°; maximum Hertz stress, 800 000 psi ($5.5x10^9$ $N/m^2$).

polyether lubricants can form elastohydrodynamic films at the cryogenic temperatures tested.

## SUMMARY OF RESULTS

Rolling-element lubrication tests were conducted with 1/2-inch- (12.7-mm-) diameter SAE 52100 steel balls. The tests were run in a NASA five-ball fatigue tester modified for cryogenic temperature testing. The test conditions included a drive shaft speed of 4750 rpm, maximum Hertz stresses of 500 000 to 800 000 psi ($3.4\times10^9$ to $5.5\times10^9$ $N/m^2$), outer-race temperatures of $160^\circ$ to $410^\circ$ R (89 to 227 K), and contact angles of $10^\circ$, $20^\circ$, $30^\circ$, and $40^\circ$. Four fluorinated polyether fluids with different viscosities were used as the lubricants. The following results were obtained:

1. Elastohydrodynamic lubrication was obtained with the fluorinated polyether lubricants at outer-race temperatures from $160^\circ$ to $410^\circ$ R (89 to 227 K), even where outer-race temperatures were lower than the pour points of the fluids.

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

3. A linear correlation was obtained for the upper-ball temperature and the lubricant temperature.

4. The upper-ball temperature increased with increasing stress at the same rate for the four fluorinated polyether fluids.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 29, 1969,
126-15.

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