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by William R. Loomis, Dennis P. Townsend
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Lewis Research Center
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TECHNICAL PAPER proposed for presentation at
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ABSTRACT

The feasibility of using presently available liquid lubricants in Mach 3 aircraft engines has been investigated with a recirculating inerted lubrication system. Three fluids performed satisfactorily for short durations of three to ten hours in a full scale simulated aircraft bearing and seal assembly at an outer race bearing temperature of 700° F. The principal problem has been with excessive leakage of the oil-side bellows face seals which has accounted for a majority of the test terminations. With only one lubricant (a MIL-L-7808E oil) could bearing failure be blamed on a lack of lubricating ability. An inerted oil-mist once-through system was also tested but with less promising results with only one lubricant running successfully at 600° F bearing temperature. The mist system appears to be limited by its inability to maintain stable bearing temperatures, but it has enough potential to justify further study.

INTRODUCTION

It is the primary purpose of this paper to report on studies of the feasibility of using some presently available lubricants in inerted lubrication systems of Mach 3 aircraft gas turbine engines. Both recirculating jet and once-through mist inerted lubrication systems were studied.

In each system, five lubricant candidates were evaluated using full scale ball bearings and mainshaft bellows face seals. In addition to inert system operational data, the discussion includes related effects of lubricant degassing and metal-oxygen reaction. Part of the studies reported herein were made under NASA Contract NAS3-6267[1-3]*. Information given in this paper will be included in reference 4.

BACKGROUND

Demands for higher bulk temperatures of aircraft turbine engine lubricating systems are primarily a result of increases in flight speeds and turbine inlet temperatures.[5,6] At aircraft speeds above Mach 2.5, as shown in Figure 1, ram air can no longer be used to cool the oil. The problem of keeping bulk oil temperatures within limits is then directly related to the amount of cooling that is available from the fuel. A serious temperature limitation is placed on the types of fluids and systems that can be considered. The ester base synthetic lubricants of conventional lubricating systems have little margin for potential use at higher temperatures.[6] Thus, there is not only an immediate need for improved lubricants and lubricating systems in uprated engines, but advanced engines, such as for Mach 3 aircraft, pose a much greater lubrication system problem because bulk temperatures are expected to be in the 450° to 500° F range.

In finding solutions to this general problem of high temperature lubrication, some attention has been given to unconventional systems such as powder lubrication,[7] dry films,[8] throwaway schemes,[9] and inerted lubrication systems.

*Numbers in parentheses designate references at end of paper.

When planning the use of liquid lubricants at high temperatures the manner in which the lubricant is apt to degrade should be considered. In a conventional open system, lubricant breakdown would probably be by fluid oxidation. The temperature limit for long term use of the diester oil formulations most commonly used in present jet engines is about 350° F. In the absence of oxidation, however, a typical diester formulation has thermal stability to about 575° F (from isoteniscope data). These data would suggest that, if we can keep oxygen from the lubrication system of an engine, the lubricant may have useful stability at temperatures over 200° F higher than if the system contained substantial amounts of oxygen.

If a lubrication system were essentially free of oxygen, however, a new set of problems might be anticipated. Oxygen in the lubrication system reacts with metals present as well as the lubricant. The metal-oxygen reaction is very necessary for lubricated parts since the metallic oxides protect the surfaces from seizure during momentary failure of the liquid film. Previous friction and wear studies (10) conducted in air and vacuum with various alloy combinations showed that the amount of oxygen in the vacuum environment needed to reform the oxide films as they wear away is extremely small, less than one part per million by volume. Figure 2 shows a plot (from ref.10) of coefficient of friction for 52 100 tool steel sliding against itself at various ambient pressures. This illustrates the point that, with limited oxygen available, as in an inerted system, more effective lubrication could result than normally encountered in an air atmosphere. However, at the lower vacuums (<10^{-6} mm Hg) where oxygen availability was appreciably reduced, the wear surfaces showed evidence of considerable metal transfer. In a closed inert gas blanketed lubrication system, it would be expected that a range of oxygen concentrations from 0.01 to 0.50 percent by volume (100 to 5 000 ppm) might effectively reduce oil oxidation and yet allow for good lubrication.

Further evidence of the effect of system operation in an inert atmosphere was shown by gear load capacity studies where this effect was found to vary with the lubricant used. Two mineral oils had greater capacities in nitrogen environment as compared to operation in air, whereas two MIL-L-7808 (diester based) and two MIL-L-9236 (polyester based) type lubricants had nearly equal gear load capacities in nitrogen and air environments.[11] In another gear study[12] a significant reduction in gear load carrying capacity for all lubricants tested (mineral oil, polyalkylene glycol, methyl chlorophenyl silicone, 5P4E polyphenyl ether, and MIL-L-23699 mixed ester) occurred when the air environment was replaced with nitrogen. The nitrogen blanketed lubricants[12] showed no increase in gear load capacity at the higher temperature levels, but in an air environment an increased capacity at higher temperatures was attributed to formation of lubricant decomposition (oxidation) products on the surface.

In ball bearing studies[13] it was found that an improvement in bearing performance occurred when the air environment was replaced with nitrogen for two lubricants (a silicone-diester blend and a MIL-O-6081-A mineral oil). Other studies have been reported in the literature (see reference 14) on boundary lubrication using inert and/or controlled atmosphere which show considerable disagreement on the effect of oxygen content on friction and wear.

Thus the literature contains apparently conflicting results on the effect of nitrogen inerting on lubrication capacity. This indicates a need for additional inert system studies by investigating candidate lubricants under simulated engine operating conditions.

EFFECT OF ENTRAINED GASES IN THE LUBRICANT

Entrained gases, particularly oxygen, in the lubricant can play a significant role in boundary lubrication, especially at high temperatures. At high surface temperatures, the chemical reaction of oxygen and water in the oil with the metal surfaces can have an effect on lubrication as previously mentioned. Degassing of the lubricant in operation could result from low ambient pressures (high altitudes) and high temperature and thereby significantly reduce its ability to lubricate.

In order to determine the influence of entrained gases on boundary lubrication, a study was made previously[15] using four lubricants in friction and wear experiments. The environment was nitrogen gas at atmospheric pressure. Friction and wear data were obtained on a 5P4E polyphenyl ether, a chlorinated methylphenyl silicone, a paraffinic resin and a polypropylene at ambient temperatures of 75°, 500°, and 1000° F with each oil in the as-received (containing normal entrained gases) or degassed conditions. Table 1 shows the amount of dissolved oxygen and nitrogen in the as-received oils as determined by a gas-chromotography technique described in reference 16. Degassing of three of the oils (silicone, resin, and polypropylene) had no appreciable effect on the friction and wear with Rene 41 sliding on Rene 41.[15] However, the polyphenyl ether appeared to be adversely affected by degassing at all three temperature levels, as shown by the results presented in Figure 3. In addition, the friction force trace obtained with degassed polyphenyl ether was markedly "rougher" as compared to the nondegassed fluid (see Figure 4). This "rough" friction trace was probably due to numerous metal-to-metal contacts occurring thru the lubricating boundary film.

A study at Pennsylvania State University[14] indicated that wear is a function of the amount of oxygen dissolved in the lubricant. In a series of experiments with a modified four-ball tester designed for use at high temperatures with controlled atmospheres, minimum wear values are obtained with oxygen concentrations far below those obtained with air as the atmosphere for a super-refined mineral oil. The amount of oxygen required for minimum wear with this type of fluid increases with increasing load. Also, it was found that for lubricants with oxygen-containing molecules, such as the diester fluid, the rate of chemical erosion involved in boundary lubrication is not as greatly affected by dissolved oxygen.

INERTED LUBRICATION SYSTEM STUDY

To gain acceptance of a concept such as inerting it is necessary to demonstrate its feasibility in full scale hardware. The problem of sealing an inert gas and a lubricant in an engine system and keeping air out is difficult in full scale hardware. Also, good sealing is critical to realizing an economical system because, if leakage rates are high, the necessary inventory of inerting gas is a weight penalty for the aircraft.

A study was made under NASA contract NAS3-6267[1-3] to determine the feasibility of using five different lubricants in an inerted recirculating lubrication system at a bulk oil temperature of 500° F with bearing outer race temperatures in the range of 600° to 800° F. A simulated engine bearing sump rig was designed and used in this investigation that incorporated 6.33-inch diameter face contact seals and a 125-millimeter ball bearing for operation at 14 000 rpm with a 3280-pound bearing thrust load. The initial bearings and seals were advanced state-of-the-art components selected from different engine development programs. Neither the bearings nor the seals were designed to operate under temperature conditions as severe as imposed by this program. Only minor changes to those components (e.g., bearing cage clearance) were made for the exploratory studies.

A schematic of the simulated turbine engine sump employing an inerted lubricating system is shown in Figure 5. Heaters on the bearing and housing O.D. were intended to permit operation to 800° F bearing outer race temperature and were used to control test cavity temperature. Hot air in the hollow main shaft was used to insure the heat flow path from the inner to outer test bearing races by maintaining an outer race bearing temperature at least 10° F higher than that of the inner race. Two face contact seals (bellows secondary) formed the sealing system. Nitrogen (oxygen content less than 10 ppm) was introduced between the two seals at 105 psig.

The seal between the nitrogen gas and the bearing sump was subjected to 100 psi pressure differential with the nominal pressure of the bearing compartment at 5 psig. The seal between the hot air (at 1200° F and 100 psig) and nitrogen was subjected to 5 psi pressure differential.

Total seal gas (nitrogen) leakage in excess of 5 scfm across both seals was arbitrarily considered unsatisfactory seal operation. Leakage from the inter-seal cavity to the bearing test chamber was monitored by injecting a known small quantity of helium into the nitrogen supplied to this cavity. Monitoring was carried out by a mass spectrometer unit drawing samples from both the inter-seal and bearing cavities. Total oxygen content of the leakage gases was not to exceed 0.5 percent.

The test bearing was a split inner ring, angular-contact ball bearing which is a type widely used in aircraft turbine engines. This design permits a maximum ball complement (because of separable inner ring halves) and supports thrust load in either direction. The separable ring also permits the use of a precision-machined one-piece cage which is required for high-speed high-temperature operation. The test bearing has a bore diameter of 125 mm and a nominal mounted operating contact angle of 26 degrees. This bearing runs at the test speed of 14 000 rpm (DN = 1.75×10^{6}) and a thrust load of 3 280 pounds (max.Hz surface stress of 197 000 psi). These conditions are typical of engine practice. For operating temperatures up to 600° F, consumable electrode vacuum melted (CVM) M-50 tool steel rings and balls were used. At higher temperatures CVM WB49 tool steel was used for the bearing rings and CVM M-1 tool steel for the balls. The cages are of an outer-ring piloted design and were constructed of silver plated M-1 tool steel. The bearings had nominal 51.6 percent inner ring and 52.1 percent outer ring conformities, four micro-inch RMS maximum cross-groove roughness, twenty-one 13/16-inch diameter balls, and 0.0068-0.0080-inch unmounted internal radial looseness.

The selection of test lubricants was made on the basis of published performance, property data, and expected performance under the experimental operating conditions. Temperature-viscosity data are given in Figure 6. The lubricants used were:

(a) Dibasic acid ester formulated with proprietary additives. This is a reference fluid that meets MIL-L-7808E specification. The viscosity variation with temperature, shown by line 1 of Figure 6, shows an extrapolated value of 0.64 cs at 600° F.

(b) Mixed ester based formulated fluid with improved thermal stability over MIL-L-7808E type fluid. It has an estimated viscosity of 1.17 cs at 600° F (line 2 of Figure 6).

(c) Synthetic paraffinic hydrocarbon containing an anti-wear additive. The viscosity is an estimated 2.4 cs at 600° F (line 3 of Figure 6).

(d) Unformulated modified polyphenyl ether (C-ether) having an estimated viscosity of 0.6 cs at 600° F (line 4 of Figure 6).

(e) Unformulated perfluorinated polymeric fluid with an estimated viscosity of 1.6 cs at 600° F (line 5 of Figure 6).

Experimental Results of Inerted Recirculating System Screening Runs

A series of three hour lubricant screening tests was attempted in the inerted recirculating lubrication system. The tests were made to explore the feasibility of using the test fluids in such a system. The running conditions were at expected environmental conditions of a bearing sump in an advanced engine. The runs were also for the purpose of identifying problems. These runs were not of sufficient duration to fully document potential problems that might accrue from extended operation with partial lubricant films. Such partial or discontinuous films might be expected at the high surface temperatures for the bearings and oil seals of these runs.

A compilation of the screening test results is given in table II, and measurements of viscosity and neutralization number for each test lubricant before and after each screening run are shown in table III. The principal results obtained for each of these degassed fluids are as follows:

(a) The MIL-L-7808E type lubricant was found not suitable, even with inert blanketing, at 600° F outer race bearing temperature. Inadequate lubrication was considered to have caused the bearing distress which included excessive wear of the cage and balls. Figure 7 shows the heavy wear encountered on these components. High oil flow rates of 4 to 5 gpm were required to stabilize bearing temperature. The lubricant's neutralization number increased significantly during the run, indicating inception of fluid degradation, but there were only minor coke deposits in the test cavity. It should be noted that this oil is limited to about 350° F bulk temperature when operating in an air environment.

(b) The mixed ester lubricant performed satisfactorily in the short tests at bearing temperatures up to 750° F. At 650° F bearing temperature, this fluid performed satisfactorily for about 10 hours before the run was stopped as a result of malfunctioning of the oil-side seal. Mass spectrometer data on the oils revealed that oil degradation at 750° F bearing temperature would preclude its use for longer periods of time than three hours, and its use should be limited to lower temperatures.

(c) The synthetic paraffinic lubricant was operated satisfactorily at bearing temperatures up to 700° F. An attempted run at 750° F was aborted after less than two hours because of excessive leakage of the oil-side test seal. Mass spectrometer data on the oil from the 750° F run indicated that significant fluid decomposition had started after one half hour of operation.

(d) The modified polyphenyl ether (C-ether) lubricant performed satisfactorily at 600° F both with and without nitrogen blanketing. Post-test inspection after both runs revealed no evidence of coking, the bearings were in very good condition (Figure 8) and the oil properties were essentially unchanged. However, it had been necessary to provide oil flows (1.2-2 gpm as compared to 0.5-1 gpm for the mixed ester and paraffinic lubricants) greater than considered practical to stabilize the bearing temperature and prevent excessive temperature excursions. Higher temperature testing was suspended because of the relatively poor bearing cooling experienced with the lubricant.

(e) The perfluorinated polymeric fluid was tested successfully to temperatures of 700° F, but higher oil flow rates were required to achieve bearing temperature stability than with the mixed ester or the synthetic paraffinic lubricants. Although the test bearings were essentially unchanged by the operation (Figure 9) there was some discoloration resulting from corrosivity of the fluid at temperatures above 600° F. Several attempts at 800° F bearing runs were unsuccessful; seal leakage rates were in excess of 5 scfm and a test bearing failed.

Only minor oil coking occurred during most of these runs and was not sufficiently serious to affect bearing or seal performance. Longer term runs of 50 hours with the mixed ester and the synthetic paraffinic lubricants were not completed due to repeated oil-side seal malfunctions, which was also the limiting factor in a majority of the three hour screening studies.

Analysis revealed that the seal malfunctions were not related primarily to the inerting gas or the thermal stability of the fluids but rather to thermal deformations, especially in the oil-side seal which accounted for about 90 percent of the leakage. A more complete discussion of the shaft seal problem is in reference 17. A continuing contract effort is intended to provide new and improved mainshaft seals for advanced air breathing propulsion. This work is under NASA contract NAS3-7609, and the first phase of this study is reported in reference 18.

The bearings performed well beyond their expectation during these short term runs with the various classes of lubricants. Four general classes of failures were observed, viz:

(a) Excessive wear of balls and cage resulting from inadequate lubrication in the ball path (such as with MIL-L-7808E oil).

(b) Gross smearing in the ball path considered to have resulted from loss of internal bearing clearance.

(c) Cage wiping (smearing) on the outer lands.

(d) Heat transfer problems (such as with the C-ether fluid) that resulted in difficulty maintaining stable bearing temperatures.

A good general reference for the analysis of the failure mechanisms in highly loaded rolling and sliding contacts, such as characterized by the first three of these listed failures, is given in reference 19. Since the longest test duration was about 10 hours in this study of inerted system lubrication, no conclusions regarding longer term operation can be drawn.

In only one case (MIL-L-7808E fluid) could bearing failure definitely be attributed to lack of lubricating ability of the lubricant. A major difficulty was with bearing cooling which appears to be a result of poor surface wetting at elevated temperatures. Table IV shows the initial decomposition temperature of the lubricants (as measured by the isoteniscope) and the inerted system screening run temperatures attained. The limited data available do not indicate any clear-cut correlation between fluid thermal stability and the lubricants' ability to operate satisfactorily at higher temperatures in short runs. Further efforts will be required to establish if such a relation does exist.

Oil-Mist Once-Through System Studies

In addition to recirculating system studies there was also an effort to study the feasibility of using conventional lubricants in an oil-mist once-through simulated aircraft inerted lubrication system. Five lubricants were tested in an inerted once-through system in three hour screening studies at the same operating conditions as the recirculating experiments. The lubricants were: (a) synthetic paraffinic hydrocarbon, (b) diester of MIL-L-7808E type, (c) polyalkylene glycol, (d) polyolefin, and (e) polyester. Two of these oils (the paraffinic and the diester lubricants) were the same oils evaluated in the inerted recirculating system. The synthetic hydrocarbon ran successfully at 600° F outer race bearing temperature, but all other runs failed by loss of internal clearances in the bearings. Excessive lubricant decomposition products were found for all lubricants except the paraffinic hydrocarbon. There was no evidence of lubrication distress in the ball tracks of mist test bearings. These results indicate that substantially higher mist-rig operating temperatures may be possible with the paraffinic hydrocarbon. Such operation would require optimized design (internal clearances and other bearing geometry), more efficient application of lubricant mist to minimize friction heat sources, and careful control of gas-mist flow to achieve stable bearing temperatures. Further developmental studies of this concept are being made to achieve more efficient application of lubricants.

SUMMARY OF RESULTS

Nitrogen gas inerted lubrication system studies were made using a simulated Mach 3 aircraft gas turbine engine sump operating at 14 000 rpm with full scale components. A 125 mm ball bearing (3 280 lb thrust load) and 6.33-inch mean diameter face contact seals were used in three hour screening studies with five lubricant candidates. The main purposes of these studies were to explore the feasibility of using an inerted system and to identify problems with 500° F bulk fluid temperatures and 600° to 800° F bearing temperatures. The experimental data and analysis revealed the following:

1. Dibasic acid ester (MIL-L-7808E) type lubricant is not suitable for 600° F bearing temperature in inerted operation because of inadequate lubricating ability. However, a mixed ester and a synthetic paraffinic fluid performed satisfactorily at 700° F bearing temperature in short duration runs. Perfluorinated polymeric fluid also performed satisfactorily at 700° F bearing temperature but higher oil flow was required than with the mixed ester and the paraffinic fluids in order to maintain stable temperature of the bearing. Also, there was evidence of corrosive attack on the bearing at higher temperatures with the fluorocarbon. A modified polyphenyl ether (C-ether) fluid operated satisfactorily at 600° F bearing temperature but was not run at higher temperatures because of apparent heat transfer problems that may be related to surface wetting deficiencies.

2. The inerted recirculating lubrication system operated satisfactorily; low oxygen content (<0.5 percent) was maintained during operation. Seal leakage was frequently so high, however, that a flight system

of these components would be impractical. This was attributed to thermal deformation of the sealing face.

3. Excessive leakage through the oil seal was a limiting factor in a majority of the lubricant studies.

4. An inerted oil-mist once-through lubrication system was tested but with less promising results than with the recirculating system. Only the synthetic paraffinic hydrocarbon lubricant of the five evaluated ran satisfactorily at a bearing outer race temperature of 600° F. The system appears to have enough potential to justify further study.

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TABLE I. - DISSOLVED OXYGEN AND NITROGEN IN AS-RECEIVED OILS AS DETERMINED BY GAS CHROMOTOGRAPHY

Lubricating fluid	Gas volume in oil at standard temperature and pressure, cc/liter	Total oxygen and nitrogen in oil, mg/liter	Oxygen in oil, mg/liter	Nitrogen in oil, mg/liter	Ratio of nitrogen to oxygen
Polyphenyl ether (five-ring isomeric)	45.9	47.25	15.95	31.30	1.96
Paraffinic resin	42.6	43.80	16.88	26.92	1.59
Chlorinated methylphenyl silicone	137.7	141.85	42.24	99.61	2.36
Polypropylene	88.3	90.80	19.80	71.00	3.59

TABLE II - SUMMARY OF TEST RESULTS IN RECIRCULATING OIL RIG

(NITROGEN BLANKETED EXCEPT WHERE NOTED)

Fluid	Run time, hr	Nominal test bearing temperature, °F	Nominal oil flow, gpm	Seal leakage, scfm	Oxygen in test sump, %	Salient conditions of test components	Results and conclusions
Diester	1.8	600	4-5	1.5-10.0	----	Oil degraded. Bearing glazed and heavy cage pocket wear.	Bearing failed. Oil not suitable for 600° F
Mixed ester	3.4	750	1.0	1.0-3.0	0.04	Some oil degradation. Slight bearing cage wiping and pocket wear.	Borderline passing at 750° F. Satisfactory for 700° F 3-hour runs.[a]
	0.2	<780	1.0	6.0-10.0	0.04	Oil degradation starting at 750° F. Bearing surface distress and heavy cage wear.	Bearing failed due to oil degradation.
Synthetic paraffinic hydrocarbon	5.4	700	1.0-1.5	2.0-3.0	0.06	All components good	Satisfactory for 700° F 3-hour runs.[a]
	1.8	750	1.0	2.0	0.09	Oil viscosity decreased.	Oil seal lift off caused excess leakage and rig fire.
Modified polyphenyl ether (N_2 blanketed)	3.0	600	1.2-2.0	7.0-11.0	0.12	Some oil degradation. Scoring of seal carbons caused excess leakage.	Required higher oil flow to stabilize bearing temp.[a]
Modified polyphenyl ether (open atmosphere)	3.2	600	1.0	2.0-12.0	20.0	Oil seals somewhat scored. Dark particles in oil but no coking.	Higher temp. testing not recommended due to oil oxidation.[a]
Perfluorinated polymer	3.7	700	2.0	15.0-23.0	0.05	Bearings discolored but otherwise unchanged. Seals good but leakage high.	Oil slightly corrosive. Required higher oil flow to stabilize bearing temperature.[a]
	0.7	740 (attempted 800)	0.5-2.0	5.0-10.0	0.05	Bearing smeared. Oil viscosity increased and oil seal worn.	Bearing failed. Higher oil flow and seal leakage than desired.

[a]Run completed desired 3-hour minimum period without component failure.

TABLE III - LUBRICANT VISCOSITY BEFORE AND AFTER SCREENING RUNS AND ACID NUMBER CHANGE

Fluid	Bearing test temperature, °F	Operating time, hr	Viscosity at 100° F, cs		Acid number change during run
			Before[a]	After	
Diester	600	1.8	12.05	12.3-12.8	100% increase
Mixed ester	600	3.3	38.9	37.4	No change
	700	3.3	38.9	46.3	Slight decrease
	750	3.4	38.9	38.3	Slight decrease
	Attempted 800	0.2	38.9	45.0	Slight increase
Synthetic paraffinic hydrocarbon	600	3.0	443.3	471.8	No change
	700-750	7.2	443.3	360.4	No change
Modified polyphenyl ether (N_2 blanketed)	600	3.0	24.8	24.9	No change
Modified polyphenyl ether (open atmosphere)	600	3.2	24.8	26.5	No change
Prefluorinated polymer	600	3.0	267.9	347.4	No change
	700	3.7	267.9	392.3	No change

[a]Values on new degassed fluids.

TABLE IV - LUBRICANT INITIAL DECOMPOSITION TEMPERATURE (BY ISOTENISCOPE)

AND SCREENING TEST RESULTS

Fluid	Initial decomposition temperature, °F (isoteniscope)	Screening run temperature, °F	
		Highest successful	Failure run
Diester (MIL-L-7808E)	575	(b)	600
Mixed ester	(a)	750	750-800
Synthetic paraffinic	600	700	750
Modified polyphenyl ether	675	600	(c)
Perfluorinated polymeric	780	700	720-780

[a] Isoteniscope data not available.

[b] No successful runs at 600° F.

[c] No runs attempted above 600° F.

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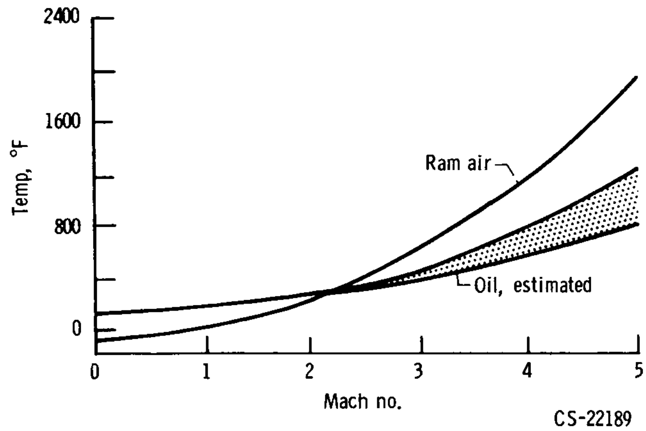

Figure 1. - Effect of Mach number on operating temperatures (from Ref. 5).

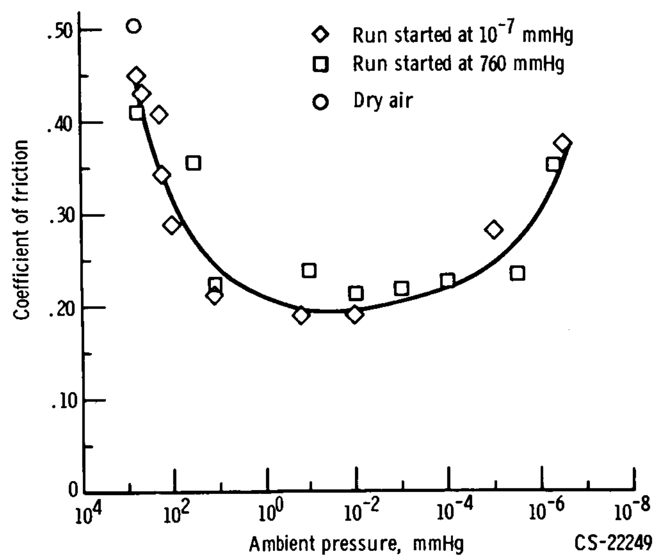

Figure 2. - Coefficient of friction for 52100 sliding on 52100 at various ambient pressures. Sliding velocity, 390 fpm; load, 1000 g; temperature, 75° F. (From Ref. 10.)

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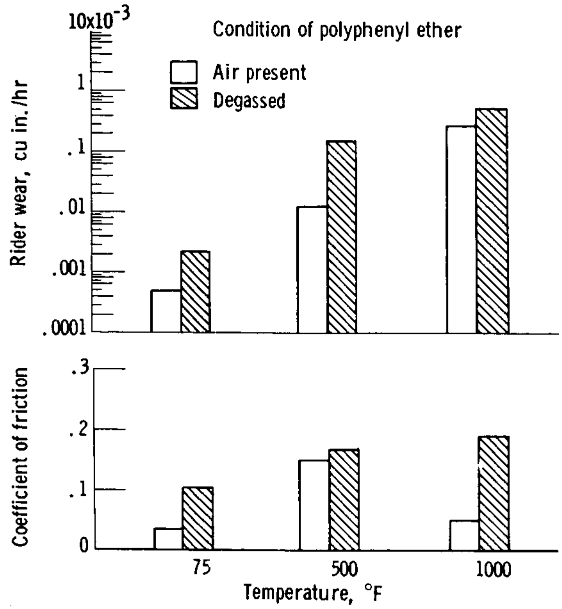
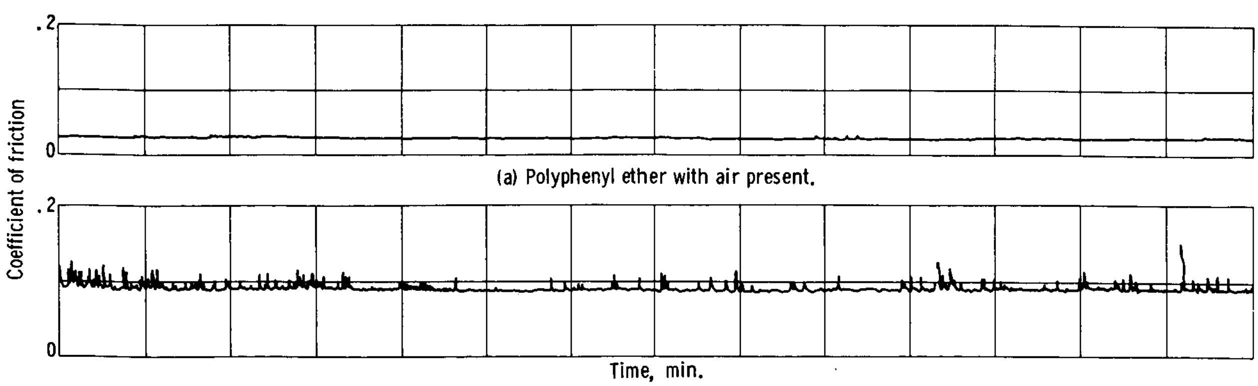


Figure 3. - Coefficient of friction and rider wear for René 41 sliding on René 41 at various ambient temperatures. Lubricant, polyphenyl ether; flow rate, 0.55 cubic centimeter per minute; atmosphere, nitrogen; sliding velocity, 4600 feet per minute; load, 1000 grams; run duration, 1 hour. (From Ref. 15.)



(b) Degassed polyphenyl ether.

Figure 4. - Coefficient of friction for Rene 41 sliding on Rene 41. Lubricant, polyphenyl ether; flow rate, 0.55 cubic centimeter per minute; atmosphere, nitrogen; sliding velocity, 4600 feet per minute; load, 1000 grams; ambient temperature, 75° F. (From Ref. 15.)

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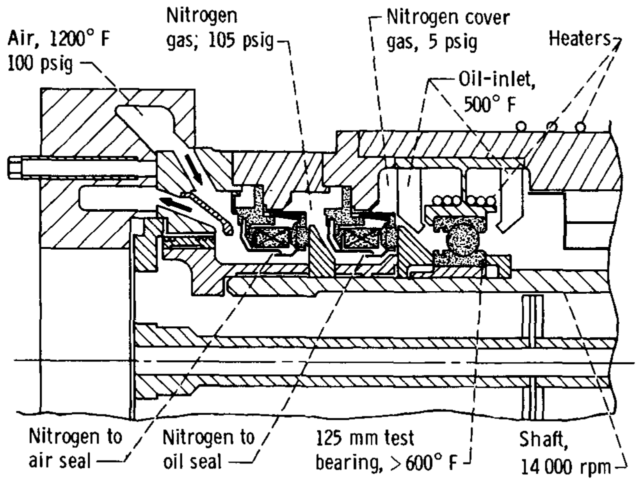

Figure 5. - Bearing and seal assembly in simulated engine sump, inerted lubrication system.

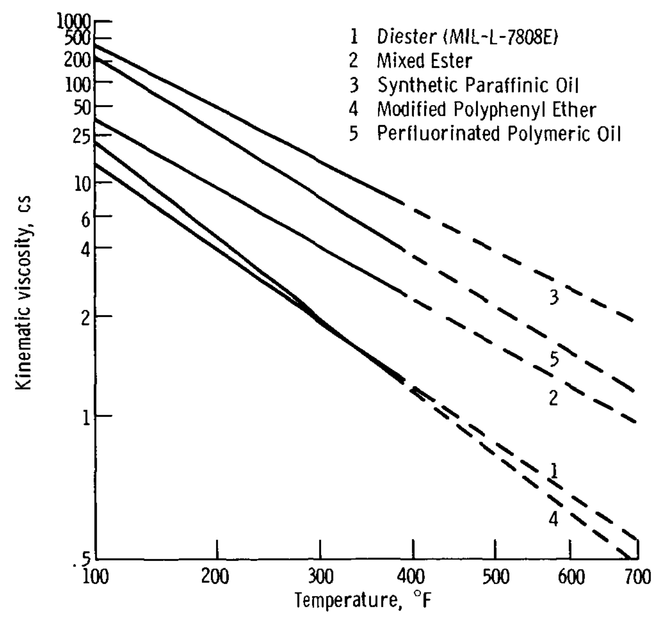

Figure 6. - Viscosity-temperature relation for recirculating oils. (Extrapolated values beyond 400° F shown as dashed lines.)

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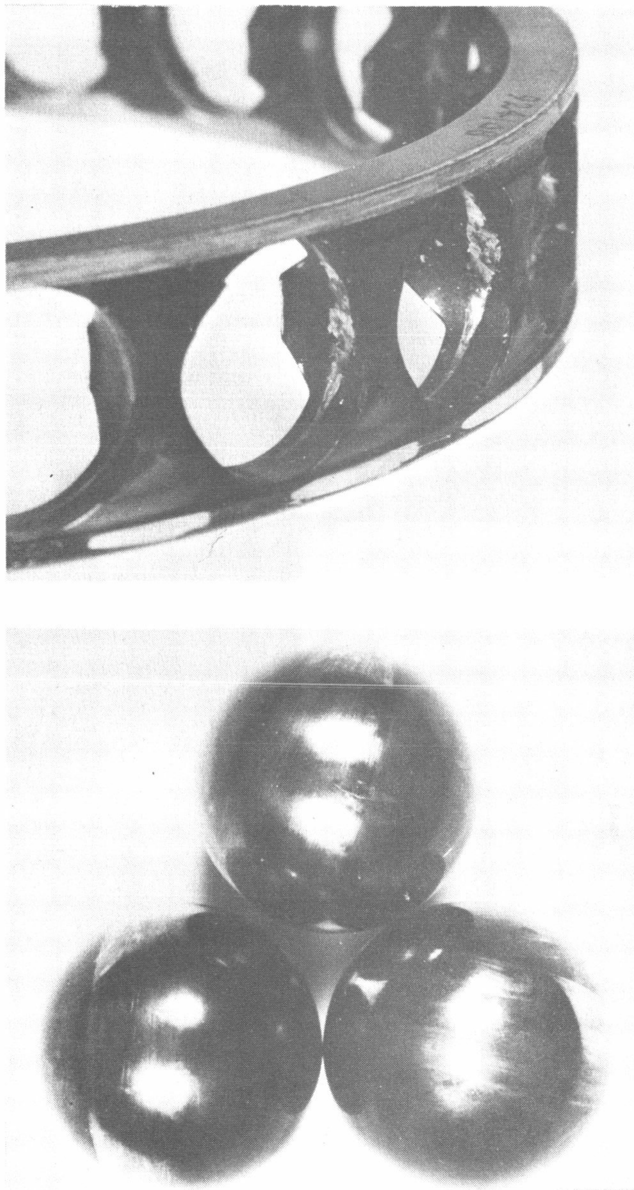

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Figure 7. - 125 mm bearing cage and balls after 1.8 hour inerted run at 600° F with Diester (MIL-L-7808E) lubricant. Note heavy cage wear and wear on balls.

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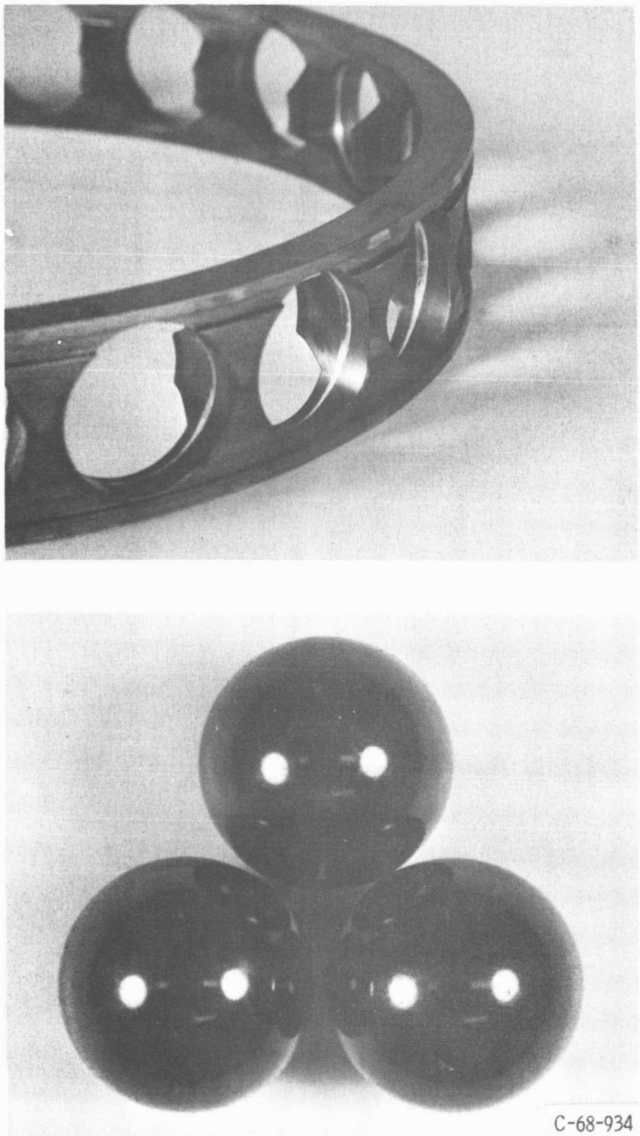

Figure 8. - 125 mm bearing cage and balls after 3.2 hour open atmosphere run at 600° F with modified polyphenyl ether lubricant. Note moderate cage pocket wear and good condition of balls.

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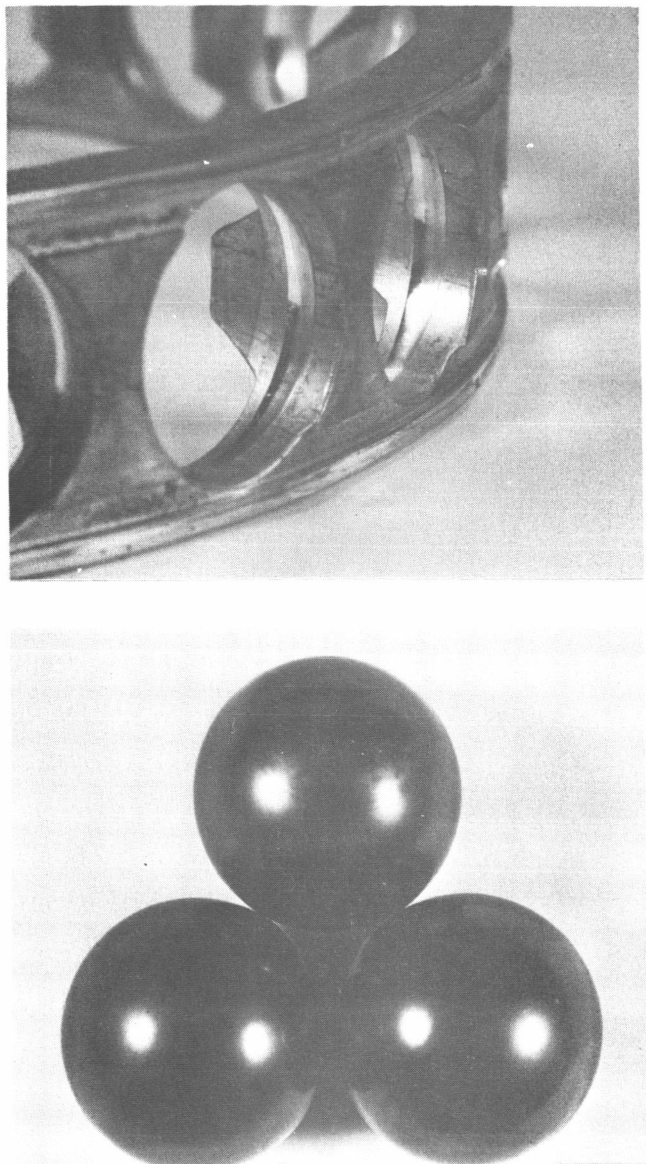

Figure 9. - 125 mm bearing cage and balls after 3.7 hour inerted run at 700° F with perfluorinated polymeric lubricant.

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