GEAR AND BEARING LUBRICATION IN EXTREME ENVIRONMENTS

By V. N. Borsoff, W. W. Kerlin, J. B. Accinelli and S. J. Beaubien
Shell Development Company

ABSTRACT

The paper describes an investigation of lubricating capabilities in bearing and gears of unsubstituted polyphenyl ethers and a comparison of these ethers with conventional lubricants. These investigations were performed under severe thermal, oxidative and ionizing radiation stresses. The results show that all lubricants suffer an appreciable decrease in load carrying capacity at elevated temperatures, but preserve their lubricating properties under the most severe environments, provided the flow of oil to the load bearing elements is not impeded. Since the flow of oil is highly affected by degradation due to heat, oxidation and radiation, the stabilities of unsubstituted polyphenyl ethers were compared in these tests to conventional oils. The results showed a great superiority of the polyphenyl ethers. It was noted also that the effect of ionizing radiation at levels below 1×10^9 ergs/g is negligibly small, and in this radiation range the main causes of lubricant degradation are heat and oxidation.

INTRODUCTION

The rapid advance in aircraft and space technology has brought many problems to the designers and manufacturers of jet engines and missile machines. One of these problems is that of lubrication at high temperatures in the presence of an oxidizing medium and ionizing radiation. Conventional lubricants cannot meet this challenge. However, research of the past few years has disclosed a few classes of fluids that have shown promise in laboratory tests for superior stabilities to heat, oxidation and nuclear radiation. Among the most promising of these new fluids is a class of compounds known as unsubstituted polyphenyl ethers. The studies of the lubricating capabilities of these fluids under extreme environments are described in this paper.

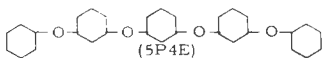
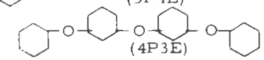
LUBRICANTS TESTED

Two of these fluids, mix-bis-(mix-phenoxyphenoxy) benzene and bis-(mix-phenoxyphenyl) ether were chosen for this investigation. For convenience the first one will be referred to as 5P4E (5 phenyl 4 ether), and the second one as 4P3E (4 phenyl 3 ether). The properties and characteristics of these fluids are discussed in detail in Reference 1. Structure and some of the physical properties of these ethers together with similar data for mineral and synthetic oils used for comparison are given in Table 1. It will be noted that the polyphenyl ethers are markedly superior with respect to thermal and oxidation stability.

TEST EQUIPMENT AND PROCEDURES

Customarily, performance capabilities of lubricants are evaluated by establishing their friction characteristics, wear protection properties, load carrying capacity, effect on fatigue life and stabilities to heat, oxidation, foaming, etc. As yet, these tests are not standardized and are performed in a large variety of bench test apparatus. All existing tests are temperature-limited and are not designed to be performed under nuclear radiation. On account of this, the over-all performance tests in equipment closely resembling the actual conditions were favored for these investigations. Gear and bearing testing machines capable of withstanding temperatures up to

TABLE 1. THE LUBRICANTS AND THEIR PHYSICAL AND CHEMICAL PROPERTIES

Lubricants	Type or Structure of Base Fluid	Pour Point, °F	Viscosity, cs		Flash Point, °F	Spontaneous Ignition Temp., °F	Initial Thermal Decomposition Temp., °F	Evaporation Loss, % by Weight		Absorption Time (hrs) of 0.5 mol of Oxygen 500 g Compound in Dornte Tests[d]		
			100°F	210°F				400°F	500°F	400°F	500°F	600°F
Mix-Bis-(mix-phenoxyphenoxy) benzene	 (5P4E)	40	379	13.4	540	1030	860[a]	-	5.1	-	>300	45
Bis-(mix-phenoxyphenyl) Ether	 (4P3E)	10	66.7	6.26	470	1080	845[a]	3.1	25.3	-	>300	60
Mineral Oil - SAE 20	White oil (highly refined)	10	76	8.8	430	-	610[b]	6[b]	-	<1.0	-	-
Mineral Oil - SAE 60	Aircraft engine base oil	10	393	26	500	-	-	1.7	-	-	-	-
MIL-L-7808C	$-(CH_2)_8-\left(\overset{O}{\overset{\Vert}{C}}-O-CH_2-\underset{H}{\overset{CH_3-CH_2}{C}}-(CH_2)_3-CH_3\right)_2$ Di-2-ethylhexyl sebacate	-75	12.6	3.30	459	710	575[a]	8.0	96.0	17	0.3	-
MIL-L-9236A	Substituted ester	-80	15.9	3.59	433	-	650[b]	5.4	53.9	-	-	12[c]

(a) Determined by Isoteniscope.
(b) Estimated from data of similar type or structure.
(c) Initial rapid oxidation followed by slow up-take of oxygen.
(d) Dornte test procedure given in Reference 5.

1000 °F were selected and installed as shown in Figure 1 in the target room of our 3-mev Van de Graaf accelerator. Due to the high radiation within the target room, the test equipment was remotely controlled from the adjacent control room.

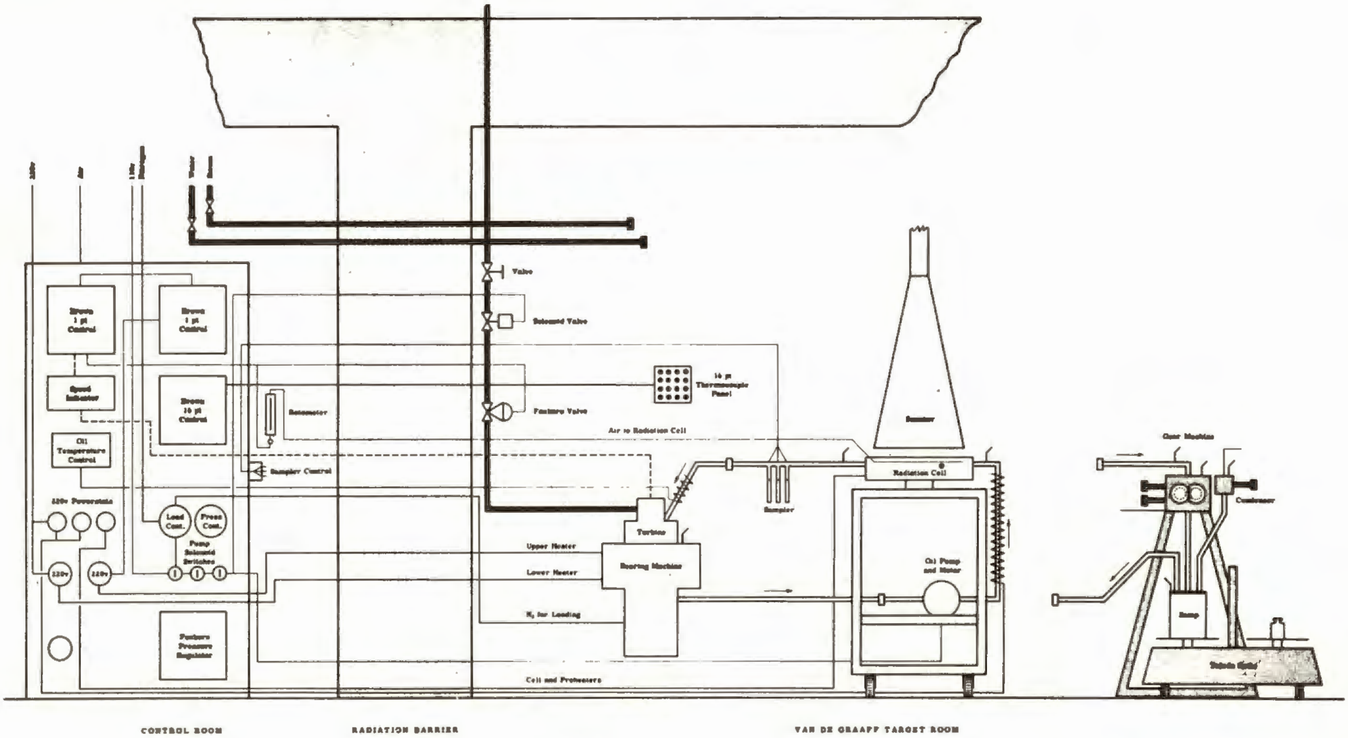


FIGURE 1. SCHEMATIC DIAGRAM OF GEAR AND BEARING TEST EQUIPMENT

Gear Machines

Three spur gear machines were used to evaluate the performance characteristics of the lubricants. These machines are of the closed-power circuit type and use the same test gears which are of 17-19 tooth combination, six diametral pitch, 20° pressure angle and 0.25 in face width. The gears are made of SAE 3312 steel, are case-hardened to 62RC and finished to 20 micro inches.

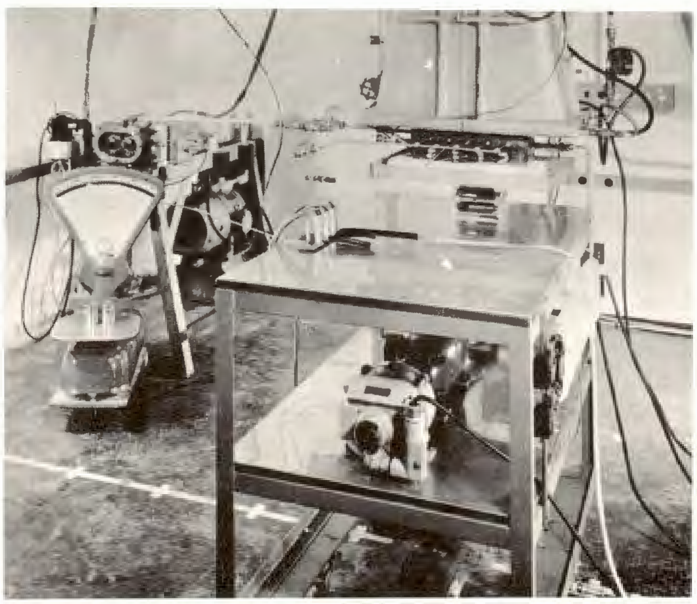


FIGURE 2. HIGH-TEMPERATURE SPUR GEAR MACHINE AND RADIATION CELL UNDER VAN DE GRAAFF ACCELERATOR

The machine selected for the over-all performance testing under electron radiation and high temperature was the high-temperature spur gear machine. This machine, as it was set up in the target room, is shown in Figure 2. The test gear chamber of this machine is separated from the supporting bearing block and is equipped with electrical heaters capable of bringing the temperature to 1000°F.

The load carrying capacity determinations at temperatures below 400°F were made in our high-speed spur gear machine described in Reference 2. Finally, all gear wear tests were performed using the radioactive gear wear test technique in a special spur gear machine. This machine and the technique are described in References 3 and 4.

Bearing Machines

The performance of lubricants in bearings at high temperatures with and without radiation was studied in both ball and roller bearing test machines. A cross section of the ball bearing machine used in the tests under electron radiation is shown in Figure 3. The lower bearing (E)

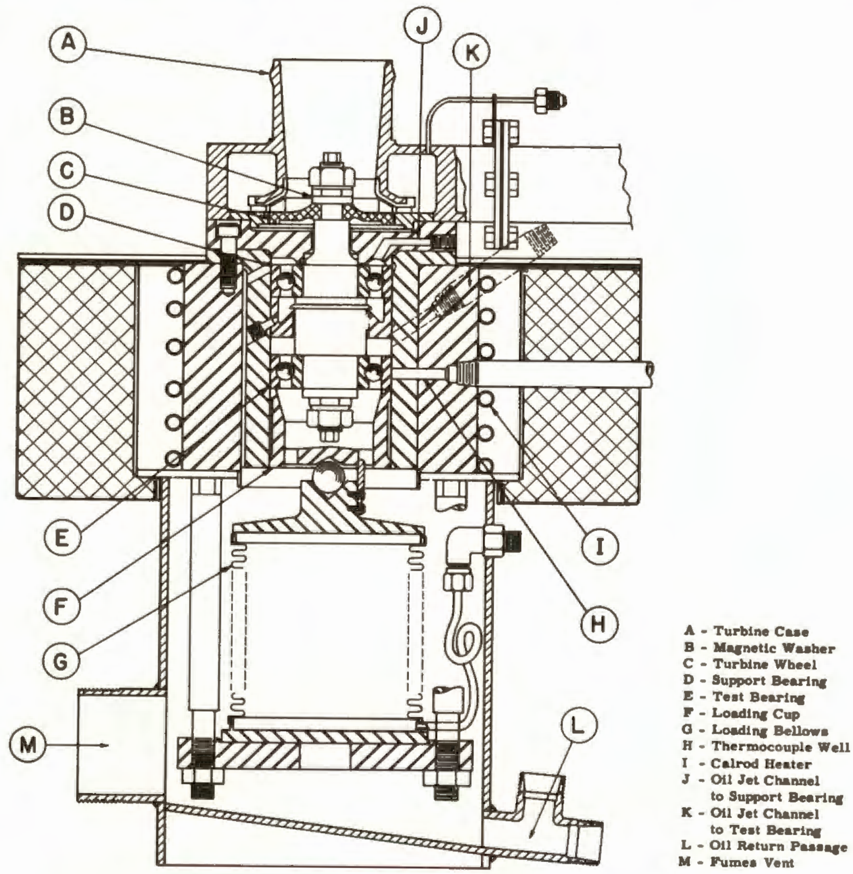


FIGURE 3. CROSS-SECTIONAL VIEW OF HIGH-SPEED HIGH-TEMPERATURE BALL BEARING RIG

is the test bearing, while the upper bearing (D) is the support bearing. Both bearings are of 25-mm size. The load is applied by a stainless steel bellow (G). Nitrogen is used to pressurize the bellows to the required load. Heating of the test bearing is provided by 4000-watt heaters. Heat travels to the bearings from the surrounding block. The bearings are driven by a small air turbine (C) having a speed range between 10,000 and 65,000 rpm. Speed is automatically controlled by regulation of the air pressure at the turbine case. Because of the low torque and the low inertia of the rotating components, the small turbine drive is particularly sensitive to friction variations. A change in friction is seen as a change in turbine drive pressure. The lubricant is supplied to the test bearing by a nozzle located in channel (K). Oil inlet temperature to the test bearing is controlled to match the bearing outer-race temperature.

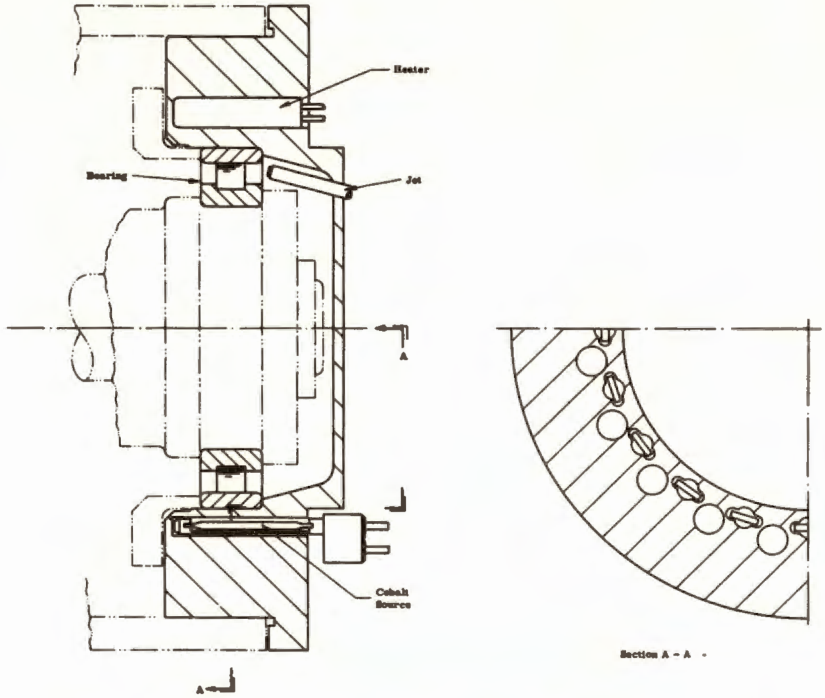


FIGURE 4. WADD BEARING HEAD WITH COBALT-60
TAPES IN PLACE

The performance of the lubricants in roller bearings with and without gamma radiation was evaluated using the 100-mm WADD bearing test machine in the cobalt-60 radiation facility at Southwest Research Institute. The test bearings used were the standard Erdco bearings made from MV-1 Latrobe steel. Figure 4 shows the bearing head with heaters and cobalt tapes. A schematic diagram of the test oil system is shown in Figure 5.

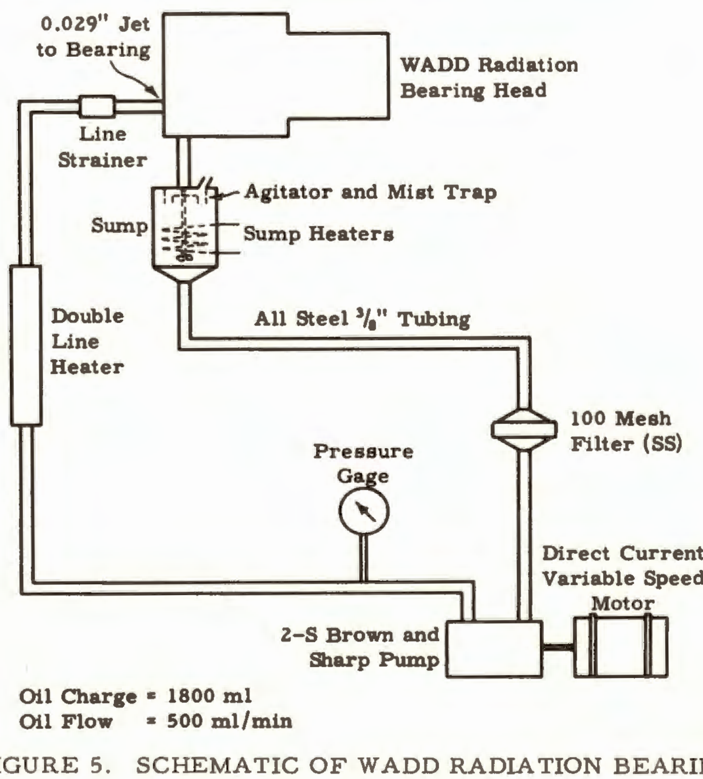


FIGURE 5. SCHEMATIC OF WADD RADIATION BEARING
RIG TEST OIL SYSTEM

Radiation and Dosimetry

A scanned electron beam from a 3-mev Van de Graaff accelerator was used in the tests with gears and ball bearings. The test oil was exposed to radiation in a special cell of three-quarter inches deep and having five injection ports for introduction of oxidizing air. This cell has a stainless steel window of 0.001 inch thick.

With a properly designed cell, and suitable sample thickness, energy absorption is independent of the target liquid and energy values need not be referred to some special dosimeter. In our case, the ceric sulfate dosimetry was used and a ceric sulfate G value of 2.17 was found for the specific conditions used. Electron dosages are reported in ergs/g.

Cobalt-60 gamma radiation performed at Southwest Research Institute in connection with roller bearing tests were calculated by cobalt glass dosimetry. The gamma dosages are also reported in ergs/g.

Test Procedures

Under electron radiation the tests consisted of operating the machines for 12 hours at the required temperature and radiation level. The rate of supply of oxidizing air in these tests was 40 ml of air per gram of lubricant per hour. The gear machine was operated at 3200 rpm and the bearing machine was operated at 40,000 rpm and 200 lb axial load.

Under gamma radiation the 100-mm WADD bearing machine was operated at 10,000 rpm and 500-lb radial load.

The lubricants tested under radiation were: 5P4E, 4P3E and Air Force reference oil MIL-L-9236A. Periodic samples of test oil were taken during each test and analyzed for viscosity, acidity and amount of unchanged oil by gas-liquid chromatography. After each gear test the last samples were also tested for load carrying capacity and wear.

In addition, several ball bearing performance tests without radiation were made, which will be described below.

RESULTS AND DISCUSSION

Gears

From our previous investigations, it was learned that viscosity is the most important score-controlling property of unreactive oils. The heavier the oil, the higher its load carrying capacity. This relation for unreactive mineral oils is shown in Figure 6. It follows that there should be a limit for the bulk viscosity at operating temperature, below which the operation of gears without scoring is impossible. This limit for unreactive mineral oils and our test gears was established as 1 to 2 centistokes. Indeed, gear geometry and construction factors, operating conditions and nature of lubricants do affect, to some extent, the magnitude of this limiting viscosity. The viscosity of 5P4E, the heaviest ether used, is 2.04 cs at 400°F and 0.86 cs at 600°F, and the load carrying capacity tests performed at 3200 rpm showed that scoring occurred with this oil on the application of the first load (288 lb per inch of face) at all temperatures above 400°F. The tests with gears at high temperatures and radiation were performed, therefore, without any applied load.

In the gear tests the temperature range covered with polyphenyl ethers was from 600 to 800°F and with MIL-L-9236A oil the temperatures were 400 and 500°F. Microscopic examinations of the gears after each test reveals that their conditions were excellent. All original grinding marks on the working surfaces were preserved and no signs of abrasive or scoring wear were noted. It appeared, therefore, that in spite of reduced load carrying capacity at high temperatures, all lubricants tested maintained their lubricating properties provided, indeed, that the supply of lubricant was properly maintained.

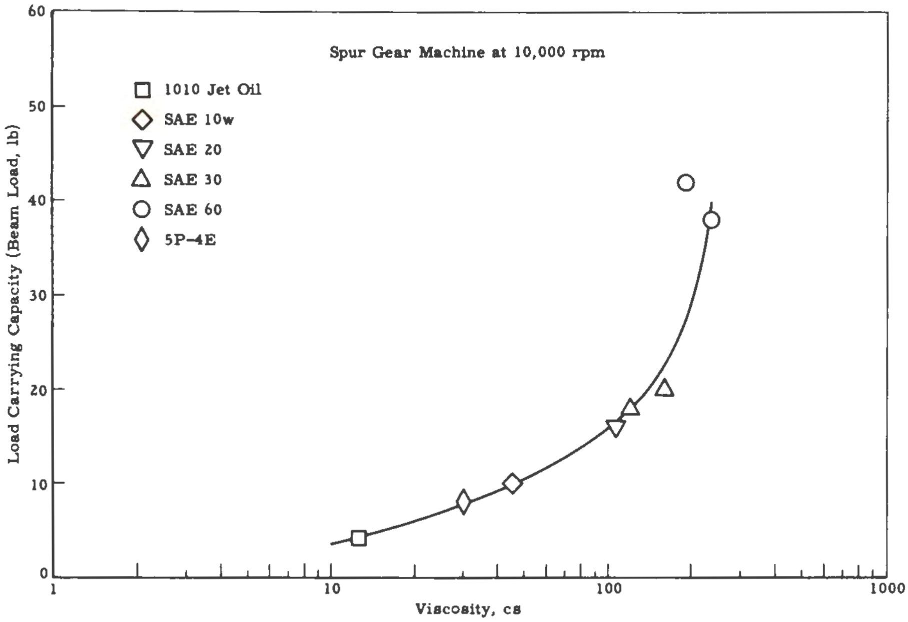


FIGURE 6. LOAD CARRYING CAPACITY OF 5P4E AND MINERAL OILS

Since degradation of lubricants could affect their flow through thickening of oil or plugging oil passages, the rates of deterioration of oils were studied. In every case the test lubricant was periodically sampled and these samples were analyzed for acidity, viscosity and amount of chemical change by gas-liquid chromatography. These results are presented in Figure 7 and show that both polyphenyl ethers are definitely superior to MIL-L-9236A oil in their stabilities to heat, oxidation and ionizing radiation. It is of interest also that at radiation levels up to 1×10^9 ergs/g the effect of ionizing radiation is small and thermal and oxidation stresses are the main contributing factors for degradation of lubricants. At radiation doses over 1×10^{10} ergs/g the effect of radiation becomes dominant.

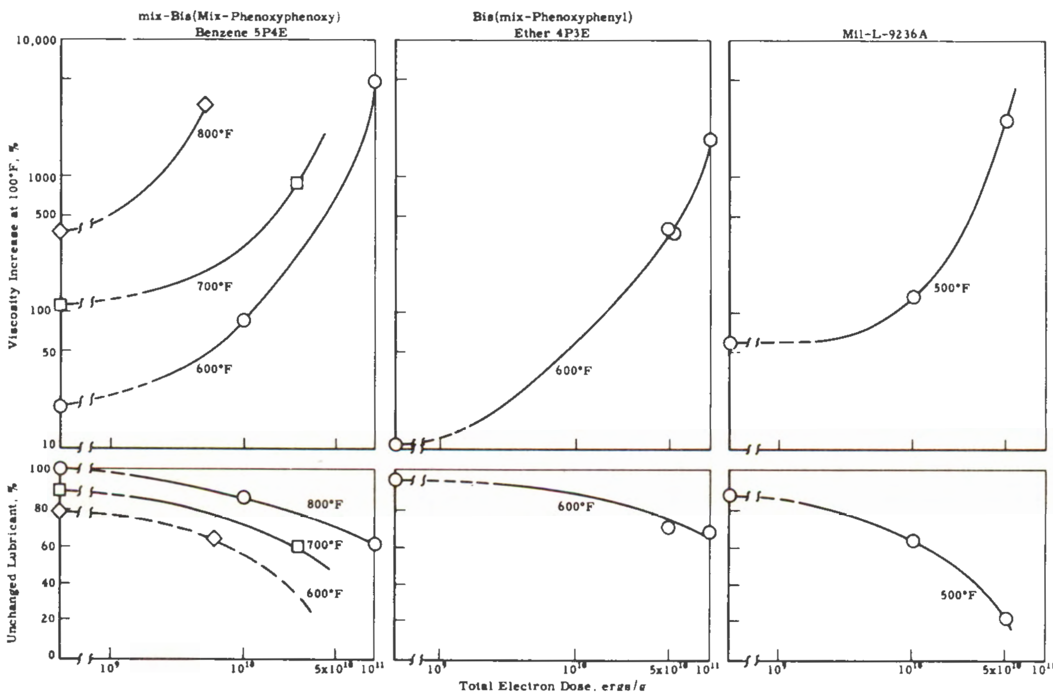


FIGURE 7. USED OIL VISCOSITY AND DECOMPOSITION AS A FUNCTION OF TOTAL RADIATION DOSE IN GEAR TESTS

The used oils were also tested for load carrying capacity and wear. The load carrying capacity tests were made in the high-speed spur gear machine at 10,000 rpm and 160°F oil temperature. The results of these tests showed that load carrying capacity of used ethers is the same as of fresh ones. This was puzzling because used ethers had, as a rule, much higher viscosities than fresh ethers. With MIL-L-9236A oil the increases in viscosity of used oils were followed by increase in load carrying capacity.

Wear was studied using the radioactive gear wear test technique. This technique consists of irradiating one of the gears and operating it with an inert mating gear under controlled conditions. Wear is detected and measured by placing a scintillation counter in the oil stream and observing the counting rate. Wear characteristics of fresh and used polyphenyl ethers, MIL-L-9236A oil and SAE 60 mineral oil at 3200 rpm and 160°F oil temperature are given in Figure 8. It is of interest that the amount of wear corresponds well with viscosities of the lubricants at operating temperature. The heavier the oil, the smaller is the wear. The exception was used 5P4E ether. It can be noted also that wear with fresh polyphenyl ethers and SAE 60 mineral oil increased by steps at the beginning of each loading period. This suggests that the mechanism of wear with these oils was a light localized scoring. With used 5P4E and MIL-L-9236A oil wear was gradual, suggesting that abrasion and scoring were intermixed. The used 5P4E ether was previously tested for load carrying capacity, and it is possible that iron particles present in this sample could have promoted an abrasive wear. With 4P3E and MIL-L-9236A oils, destructive wear (scoring) was reached at a load of 1730 lb/in. of face, and with fresh 5P4E and SAE 60 mineral oil at 2300 lb/in. of face.

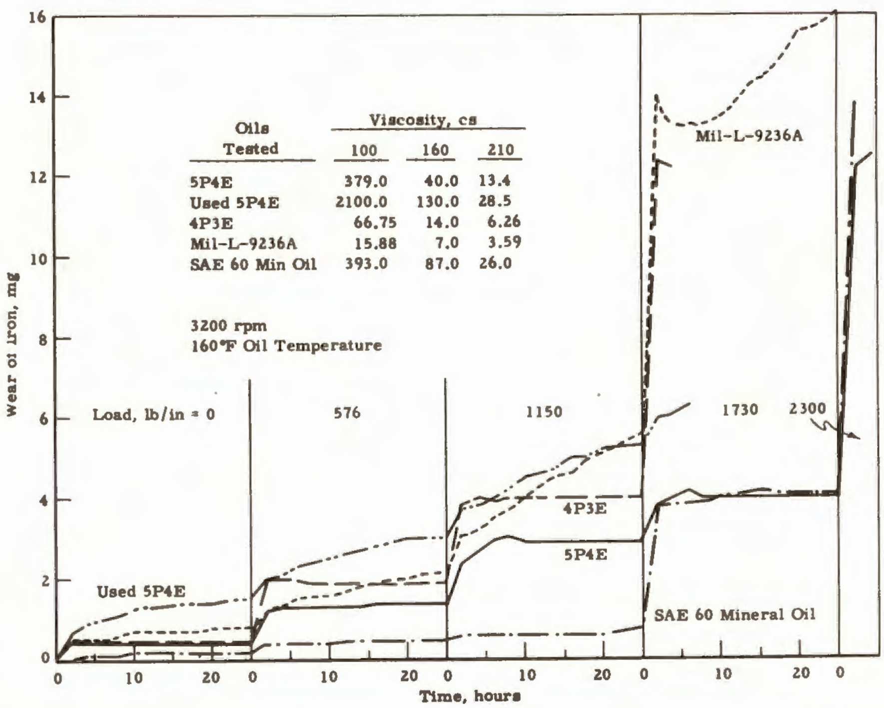


FIGURE 8. GEAR WEAR AS A FUNCTION OF TIME AND LOAD WITH RADIOACTIVE GEARS

Bearings

The frictional behavior of ball bearings with different oils was first investigated without ionizing radiation. In this work the oil was applied in a once-through system in order to minimize the effect of deposits. The bearings were operated at 60,000 rpm, 200-lb axial load and the test temperature was increased by steps up to 900°F. The results, given in Figure 9, show all fluids at first give decreasing friction with increasing temperature, followed by a relatively rapid rise in friction as the temperature is further increased. The minimum point for these curves is referred to as the friction-limited temperature of the lubricant, and it appears that it signifies a change from largely hydrodynamic to boundary lubrication. It is of interest that in the hydrodynamic region the bearing friction corresponds with lubricant viscosity and that the friction-limited temperatures of

5P4E, MIL-L-7808C and white mineral oil were about the same (approximately 800°F). This suggests that in high-speed, high-temperature ball bearing service, 5P4E exhibits frictional characteristics which are at least equivalent to other lubricants accepted in the field.

Another phase of the high-temperature investigations was the study of the effects of recirculation of the lubricant on performance. In these tests, the bearing outer-race and the incoming oil jet were kept at the same temperature. The rest of the circulating system operated at some 300°F below the bearing temperature. Thus, the total residence time at the test temperature largely controlled the thermal and oxidative breakdown of the oil. A convenient measure of this total hot zone residence time is the number of times the oil is recirculated through the system. This is given in the results as number of passes through the hot zone, a parameter that is of general interest because it includes sump volume, flow rate and operating time. While this approach is not rigorous, it provides a practical yardstick for judging the useful life of the lubricant.

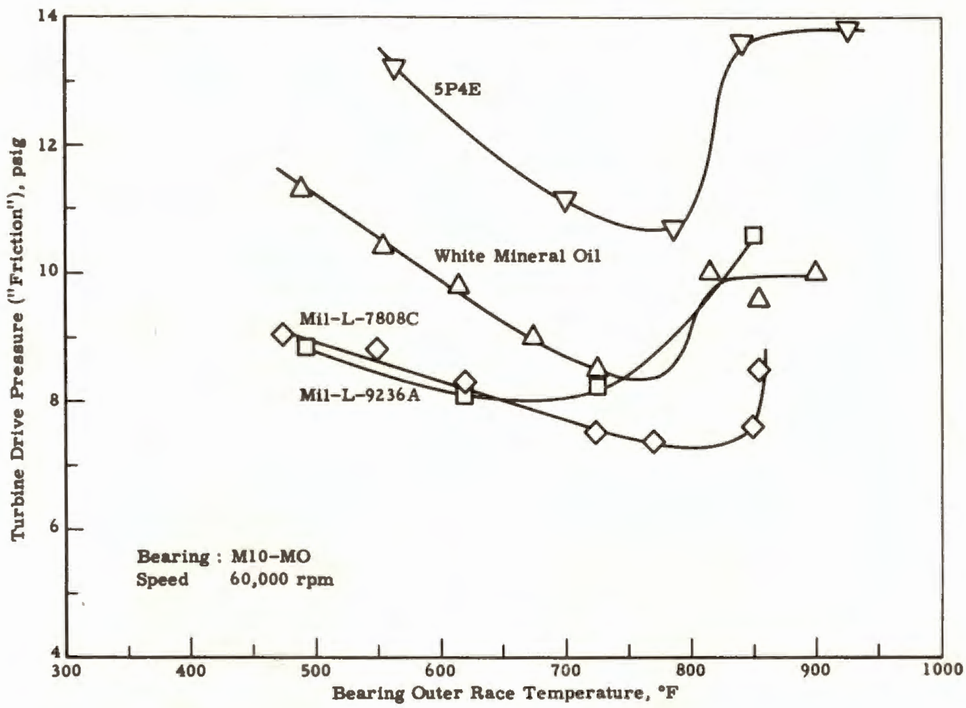


FIGURE 9. BALL BEARING FRICTION AS A FUNCTION OF BEARING OUTER RACE TEMPERATURE FOR VARIOUS LUBRICANTS

These experiments were performed at 60,000 rpm, 200-lb axial load and ambient temperature of 700°F. Figure 10 shows how the friction increases with number of passes through the hot zone for white mineral oil, 5P4E, and the two MIL specification oils. In each case the test was terminated when friction began to increase rapidly. 5P4E, at 110 passes, was 5 to 10 times better than the mineral oil or the MIL-L-9236A fluid. The test with MIL-L-7808C oil was discontinued at about half the 5P4E life because of excessive evaporation of the fluid; however, friction had already begun to increase at the time. Table 2 shows the changes in lubricant properties, the iron content, bearing condition and deposits at the end of the test. The bearing deposits are shown in the photographs of Figure 11. All these data indicate the superiority of 5P4E ether over the other fluids.

The tests under electron radiation with ball bearings were performed with 5P4E at temperatures up to 800°F, with 4P3E at 600°F and with the Air Force reference oil MIL-L-9236A at 500°F. Besides the data on the degradation of these oils, frictional behavior of the bearings and their conditions after the test were observed.

Similar to the gears, the bearing operated successfully under these extreme environments, provided the supply of lubricant was properly maintained. The data on degradation of fluids is

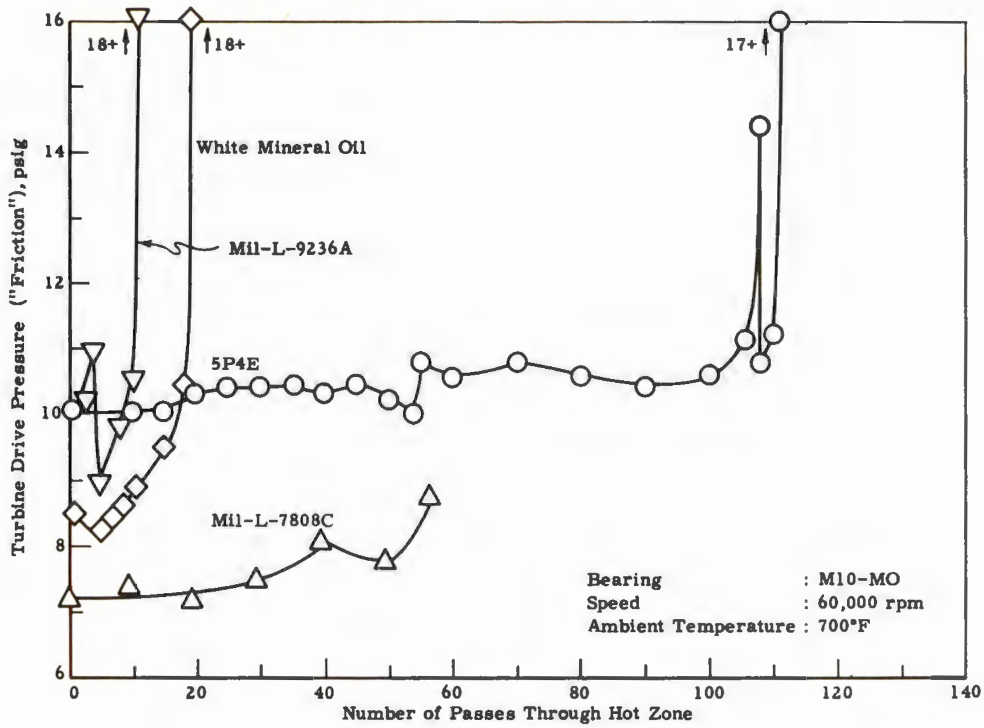


FIGURE 10. BALL BEARING FRICTION AS A FUNCTION OF NUMBER OF PASSES OF THE LUBRICANT THROUGH THE HOT ZONE FOR VARIOUS LUBRICANTS

a. Mineral Oil, 19 Passes

b. MIL-L-7808C, 57 Passes

c. MIL-L-9236A, 11 Passes

d. Mix-5P4E, 110 Passes

Bearing : M10-MO
Speed : 60,000 rpm
Load : 200 lb Axial
Lubricant Flow : 70 g/min, Recirculating

FIGURE 11. CONDITION OF BEARINGS LUBRICATED WITH VARIOUS LUBRICANTS AT AN AMBIENT OF 700°F

TABLE 2. SUMMARY OF OIL CHANGES AND BEARING CONDITION

High temperature ball bearing tests without radiation
recirculating oil system

700°F, 60,000 rpm

Lubricant	No. of Passes	Increase in Viscosity at 100°F %	Increase in Acidity, mg KOH/g	Iron Content, ppm	Bearing Inspection Condition	Bearing Inspection Deposits
White Mineral Oil	20	50	.56	1.9	Good	Med. heavy
MIL-L-7808C	57	290	29.17	38.2	Pitted	Med.
MIL-L-9236A	11	15	3.93	133	Wear bands	Very heavy
5P4E	110	10	nil	3.4	Good	Med. heavy

therefore of importance. These data are shown in Figure 12. As in the case of gears, the polyphenyl ethers showed a superior stability to MIL-L-9236A fluid. Figure 13 summarizes the friction results. Here, turbine drive pressure at the end of each test is plotted as a function of total radiation dose for the three lubricants at the test temperature indicated. At 600°F, 5P4E showed no increase in friction up to 1×10^{11} ergs/g. At this temperature, 4P3E failed at a total radiation dose of 5.4×10^{10} ergs/g. By contrast, the MIL-L-9236A oil failed after 11 hours with 5×10^{10} ergs/g and temperature of only 500°F.

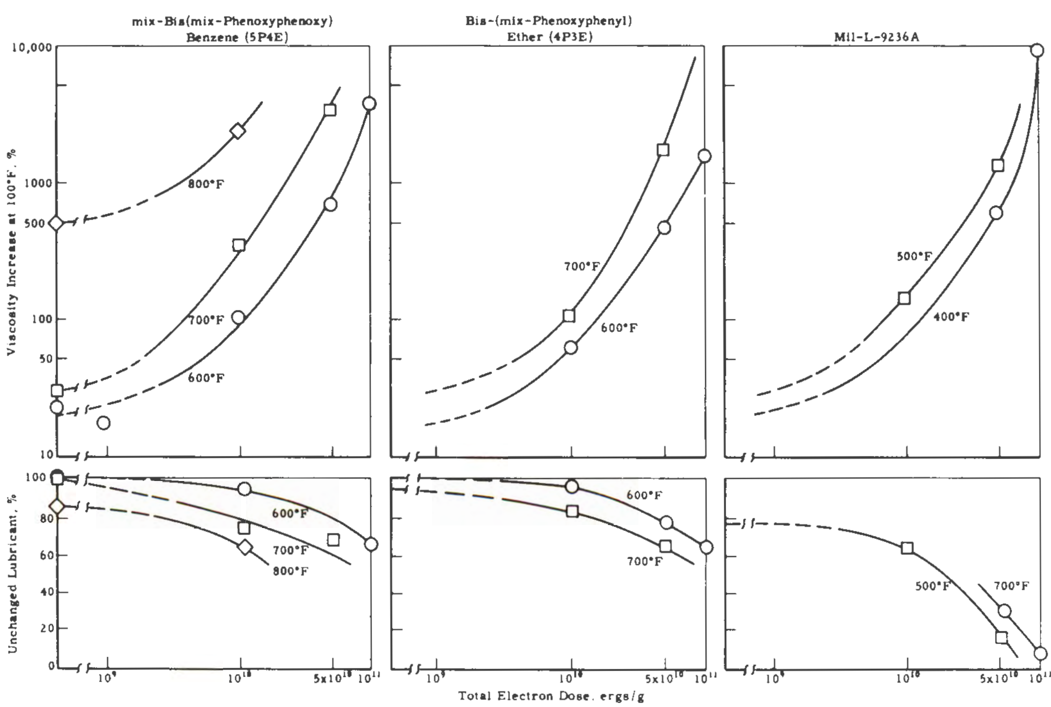


FIGURE 12. USED OIL VISCOSITY AND DECOMPOSITION AS A FUNCTION OF TOTAL RADIATION DOSE IN BALL BEARING TESTS

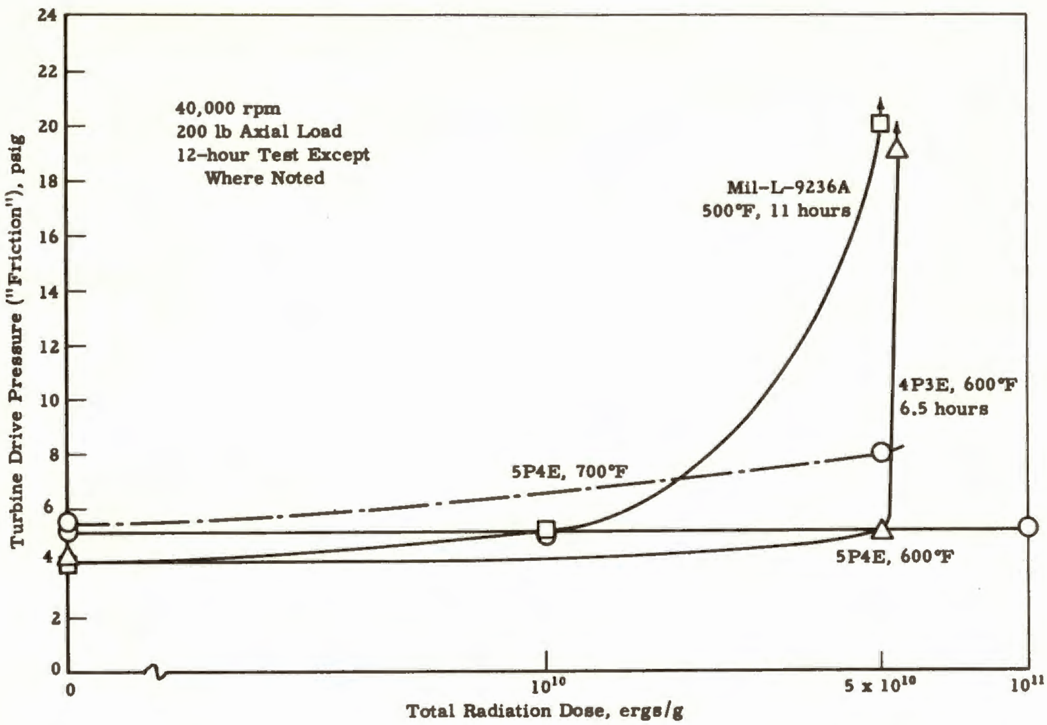


FIGURE 13. BALL BEARING PERFORMANCE AS A FUNCTION OF TOTAL RADIATION FOR DIFFERENT LUBRICANTS

Roller Bearings

The tests were conducted under gamma radiation in the WADD 100-mm bearing rig by Southwest Research Institute. The data is presented in Table 3. 5P4E provided adequate lubrication throughout the 100 hours of operation at 600°F and exposure to a total radiation dose of 4.3×10^9 ergs/g, while under similar conditions MIL-L-9236A fluid lasted only 17 hours. At 400°F and 4.3×10^9 ergs/g, the MIL-L-9236A fluid provided adequate lubrication, and was, under these conditions, roughly equivalent to 5P4E at 600°F.

TABLE 3. RESULTS OF 100 MM ROLLER BEARING TESTS AT SOUTHWEST RESEARCH INSTITUTE

Lubricant	5P4E		MIL-L-9236A		
Temperature, °F	600		400		600
Radiation Dose	0	4.3×10^9 ergs/g	0	4.3×10^9 ergs/g	0
Time-hrs	100	100	100	100	17
Inspections					
System Deposits	Clean	Medium in bearing and housing. Line and filter - clean	Clean	Clean	Heavy in bearing and housing. Filter plugged.
Weight loss of bearing outer race, mg	14.6	16	Negligible	Negligible	12.4
% Increase in viscosity at 100°F of used oil	25	46	19*	6*	Jell-like consistency

*Low value probably results from addition of make-up oil just prior to end of test.

CORRELATIONS

It is of interest to note that a good correlation exists between various tests performed under electron and gamma radiation. As an example, results obtained with 5P4E at 600°F are shown in Figure 14. Here, viscosity (measured at 100°F) is plotted as a function of total radiation dose. The graphs for each of the tests are alike.

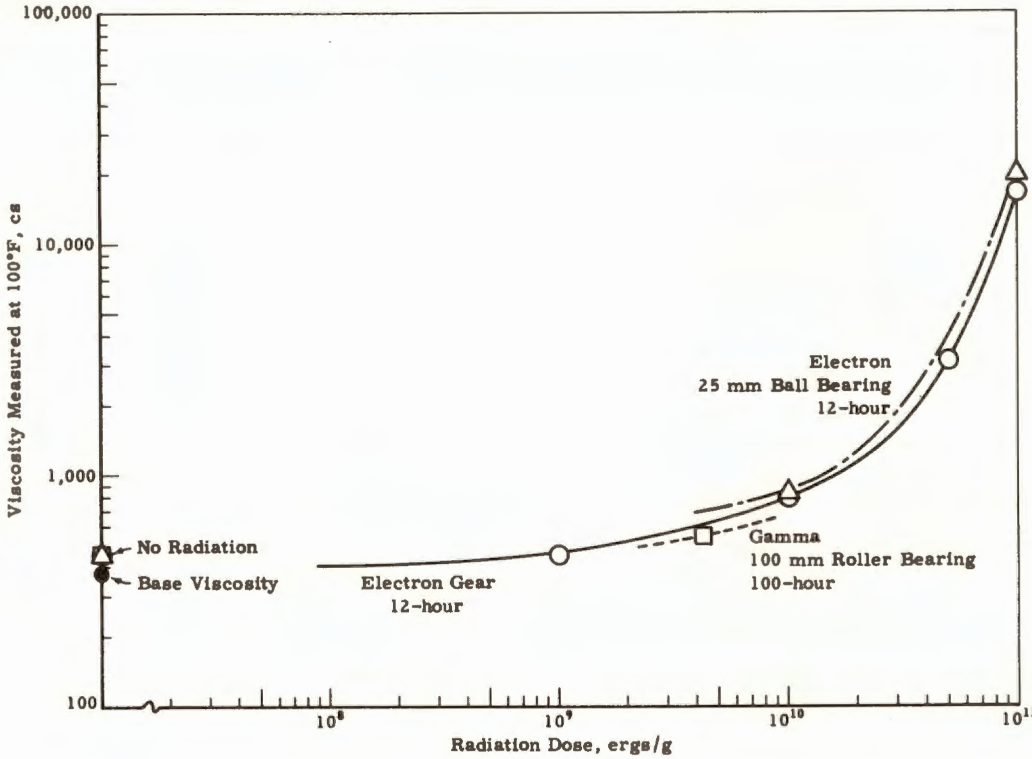


FIGURE 14. COMPARISON OF VISCOSITY CHANGES OCCURRING IN 5P4E DURING DYNAMIC TESTS WITH ELECTRON AND GAMMA RADIATION AT 600°F

CONCLUSIONS

In the various gear and bearing systems used in this study the following conclusions appear to be justified:

(1) The lubricants tested preserved their lubricating properties under severe thermal, oxidizing and ionizing radiation environments, provided the supply to the working surfaces was maintained uninterrupted.

(2) The proper flow of lubricants is usually impeded through degradation of the lubricants themselves. Therefore, the stability of lubricants to heat, oxidation and ionizing radiation is an important factor.

(3) The polyphenyl ethers are superior to the conventional lubricants (represented here by MIL-L-9236A oil). Very generally, the temperature advantage of polyphenyl ethers is about 200°F and its resistance to ionizing radiation is about 10 times higher than that of conventional oils.

(4) At radiation levels up to 1×10^9 ergs/g, the effect of ionizing radiation is small. Thermal and oxidation stresses are the main contributing factors for degradation of oils. At radiation doses over 1×10^{10} ergs/g, the effect of radiation becomes dominant.

(5) All unreactive lubricants suffer a decrease in load carrying capacity with increase in temperature.

(6) It appeared that friction, load carrying capacity and wear with polyphenyl ethers are similar to those of unreactive mineral oils of comparable viscosity at the operating temperature.

(7) Degradation of the unsubstituted polyphenyl ether by radiation was the same for the various systems studied. This included large and small bearings as well as spur gears and both gamma and electron radiation.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to C. L. Mahoney, E. R. Barnum and C. D. Wagner of Shell Development Company for their contributions as well as to Materials Laboratory, Wright Air Development Division, and Bureau of Naval Weapons, Department of the Navy, for permission to publish this paper.

LIST OF REFERENCES

1. Mahoney, C. L., Barnum, E. R., Kerlin, W. W. and Sax, K. J., ASLE Transactions, Vol. 3, 1960.

2. Borsoff, V. N., "On the Mechanism of Gear Lubrication," ASME Transactions, Series D, March 1959, pp 79-93.

3. Borsoff, V. N., Cook, D. L., and Otvos, J. W., "Tracer Technique for Studying Gear Wear," Nucleonics, Vol. 10, No. 10, October 1952, pp 67-69.

4. Borsoff, V. N., "Wear Studies with Radioactive Gears," Lubrication Engineering, Vol. 12, No. 1, Jan.-Feb., 1956, pp 24-28.

5. Dornte, R. W., Ind. Eng. Chem., Vol. 28, No. 26, (1936).