BEARING LUBRICATION WITH ADDITIVE FUEL

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ABSTRACT

A report is made on the progress of an investigation conducted to determine the feasibility of using JP-5 fuel plus an additive as a lubricant for turbojet engine bearings. Results of both bearing rig testing and J65 turbojet engine operation are presented.

INTRODUCTION

A number of publications in recent years have described the satisfactory results obtained with high-temperature bearing operation in the absence of liquid lubricants.(1, 2) A review of past Air Force-Navy-Industry conferences and the literature suggests that a practical application of this unique method of bearing lubrication would be jet engine operation. At this time we would like to report on the progress of an investigation which has been conducted by the Aeronautical Engine Laboratory at the Naval Air Material Center, to determine the feasibility of using jet fuel with additives for lubricating high-speed jet engine bearings in the 500 to 600°F temperature range. The use of fuel with additives to provide lubrication is an application of the principle that a suitable means of lubricating at high temperature could be achieved by using a fluid or carrier which would volatilize on the bearing, thus providing some cooling and an antiscuff additive or extreme pressure additive be carried in the fluid to keep the bearing from seizing. Studies of the lubricant chemistry associated with bearing surface phenomena of film formation have been made. Although various theories have been advanced in the literature, the exact chemical mechanism is unknown. It is known, however, that through additive action, friction and wear can be reduced provided the additive forms a suitable coating on the metal surfaces. The function of the coating or film is to separate the two metal surfaces so that in rubbing they do not gall or seize. Some additives have an affinity for the bearing surfaces and adhere to them, forming their characteristic chemical coating. Other extreme pressure additives which are hydrocarbon compounds and contain a metalloid atom such as sulfur or phosphorus, are known to react with steel surfaces. Beeck(3) has explained the action of these compounds as follows: they are stable at room temperature but at elevated temperatures decompose and release the free metalloid atom. Where metal-to-metal contact occurs, the local temperature rises and the resultant decomposition of the agent releases some of the metalloid, which then attacks the metal over the rubbing area to form a thin easily sheared coating of the compound of the metal and metalloid; e.g., the metal sulfide or phosphide.

For years it has been the practice in boundary lubrication to prevent scuffing by films generated on the working surfaces by extreme pressure additives such as sulfur, phosphorus, and chlorine alone or in combination. This was the guide used during the investigation for a jet engine bearing additive-fuel lubricant. The additives were "off the shelf" compounds containing phosphorus, and/or sulfur, or chlorine. Jet fuel MIL-J-5624 JP-5 type was selected for the additive carrier as this type of fuel probably will be burned in jets for some time to come. One of the possible applications of the additive fuel lubricant is aircraft; a weight saving is envisioned with JP-5 already aboard by using the plane's fuel tanks for a supply of fuel and mixing the additive prior to delivery to the bearing jet.

PHASE I - RIG TEST TO SIMULATE J65 CONDITIONS

The first phase of this work was to evaluate a number of fuel-additive lubricants for their deposition characteristics and load-carrying ability. A small bearing test rig was constructed to operate a No. 204 size ball bearing at 10,000 rpm and 600°F outer race temperature.(4) No external load was applied during the test. Test duration was 6 hours. If the deposits were acceptable and the bearing was satisfactory as evidenced by a spin test, the fuel additive lubricant was further evaluated in the high-temperature loaded bearing rig. This machine was designed and constructed in order

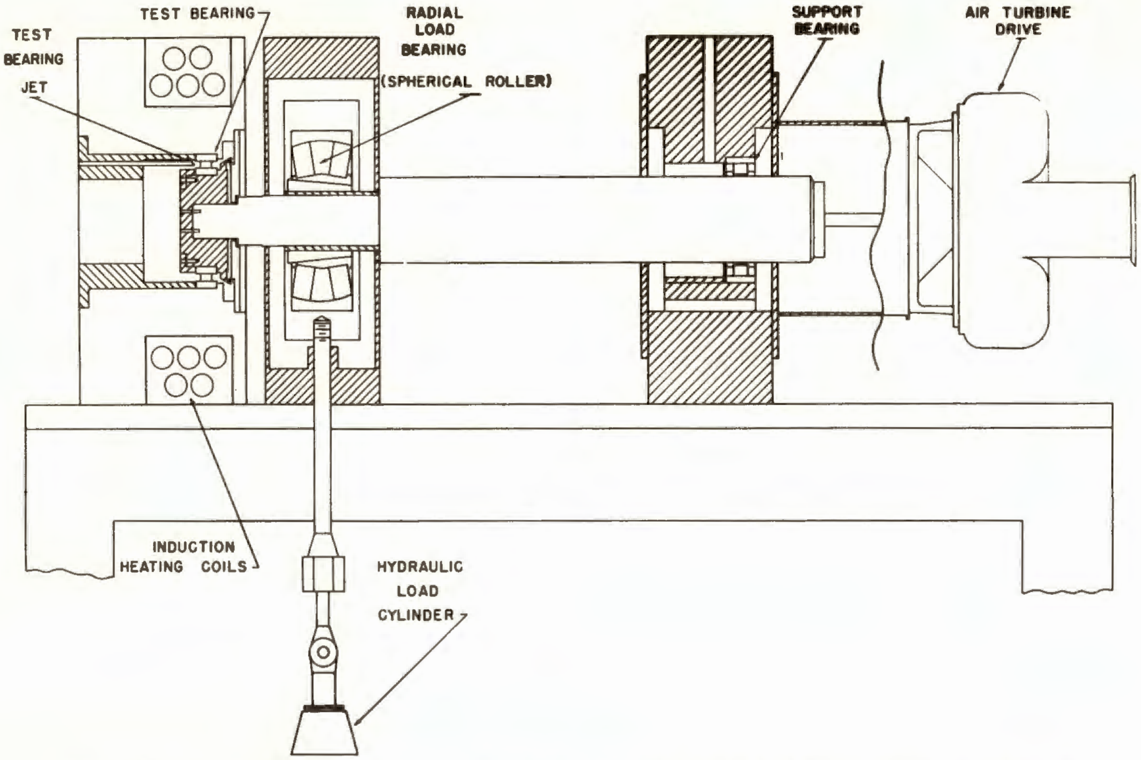
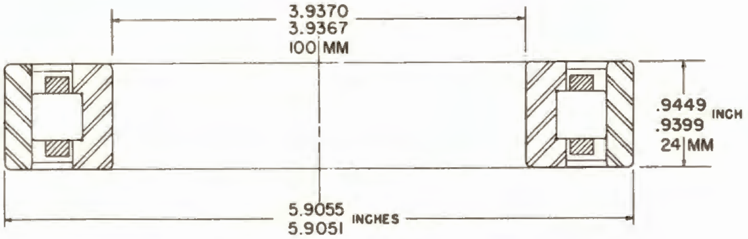


FIGURE 1. AERONAUTICAL ENGINE LABORATORY HIGH-TEMPERATURE BEARING RIG

RACES & ROLLERS MV-1 LATROBE STEEL

RETAINER "ROLLUBE" IRON TWO PIECE RIVETED



24 ROLLERS $\frac{7}{16} \times \frac{7}{16}$ (CROWNED)

DIA. WITHIN .000025 OF EACH OTHER IN ANY ONE BEARING

RBEC-5 SPECIFICATION

INTERNAL RADIAL CLEARANCE (UNMOUNTED) .0024-.0034

FIGURE 2. ERDCO TEST BEARING

TRI-P-TOLYL THIOPHOSPHATE

$(CH_3C_6H_4O)_3PS$ .... MW 384.44

FIGURE 3. TRI-P-TOLYL THIOPHOSPHATE - CHEMICAL FORMULA

to test the additive-fuel lubricants for their load-carrying ability at conditions which nearly simulate the J65 center and rear main bearing operation.

Figure 1 is a cross-section drawing of the Aeronautical Engine Laboratory's high-temperature loaded bearing rig. This machine is driven by an air turbine shown on the right. The center bearing, a spherical roller type, transfers to the shaft the radial load applied by the hydraulic cylinder. The test bearing at the left of the figure is assembled on the shaft by means of an adapter. External heat is applied to the test bearing by the induction heating coils.

The test bearing (Fig. 2) is a 100-mm roller type. Races and rollers are made of MV-1 Latrobe steel. The retainer or cage is "Rollube" iron two-piece riveted. Twenty-four rollers, 7/16 by 7/16, are assembled in the bearing. The cage "rides" or is guided by the inner race. Bearing dimensions are 100-mm inside diameter, 150-mm outside diameter and 24-mm wide. A new test bearing is installed in the rig and run in for 4 hours at 400°F using MIL-L-7808 lubricating oil, prior to the run with an additive-fuel combination. The break-in run was deemed necessary after early tests indicated longer periods of rig operation resulted with the run-in.

Table 1 shows the Aeronautical Engine Laboratory high-temperature bearing rig operating conditions with 100-mm Erdco bearing. The test lubricant was considered satisfactory if 100 hours of intermittent operation at these conditions were achieved, and the bearing did not exhibit excessive cage wear or pitting and scuffing of the rollers and races.

TABLE 1. J65-W-4 TURBOJET TYPICAL OPERATING CONDITIONS

Lubricant to No. 2 and No. 3 Main Bearings - JP-5 + 1% Tri-P-Tolyl Thiophosphate

	Speed, rpm	Thrust, lb	Exhaust Gas Temperature, °F	No. 2 Bearing Outer Race, °F	No. 3 Bearing Outer Race, °F	No. 2 & 3 Bearing Compartment Ambient, °F
Military Rated	8300*	7400	1185	465-475	485-505	565
Normal Rated	8000	6500	1080	450	475-485	540
90% Normal Rated	7760	5800	985	440	450	510
Idle	3880	450	990	150	160	200

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* DN = 1,000,000

Out of a total of 16 additive fuels evaluated in the high-temperature loaded bearing rig, only one type to date lubricated the test bearing for 100 hours. This combination was JP-5 plus 1% by weight of tri-p-tolyl thiophosphate. On a run using 0.5% of the additive to obtain data at a lower concentration, heavy cage wear developed after 30 hours of operation. Figure 3 depicts the chemical formula. This material is powder in form and does not readily go into solution with JP-5. However, the 1% concentration of tri-p-tolyl thiophosphate is first dissolved with 1% by weight benzene in which it is soluble. Then the blend is added to the JP-5 fuel to be used as a lubricant.

Figure 4 is an end view of the Erdco test bearing after 100 hours of operation with JP-5 plus 1% tri-p-tolyl thiophosphate. This shows the appearance of the test bearing assembly as it was removed from the rig. Carbon deposits were heavy. Figure 5 is a close-up view of a section of the rollers and cage. Most of the carbon particles which adhered to the rollers were flaky and were easily removed by a cotton cloth. Figure 6 is a close-up view of a portion of the outer race of the test bearing. The track area is in excellent condition. The heavier carbon build-up is on the jet side of the race. Some of the deposits were unintentionally removed as the roller assembly was withdrawn from the outer race. The dark vertical lines across the track area are carbon smudges made by the rollers at disassembly.

FIGURE 4. ERDCO TEST BEARING AFTER 100 HOURS OF RUNNING

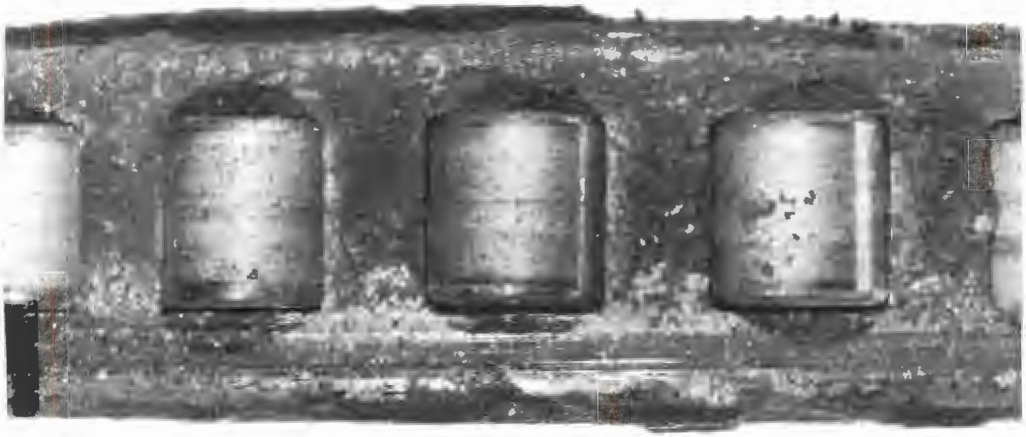

FIGURE 5. CLOSE-UP VIEW OF ROLLERS AND CAGE

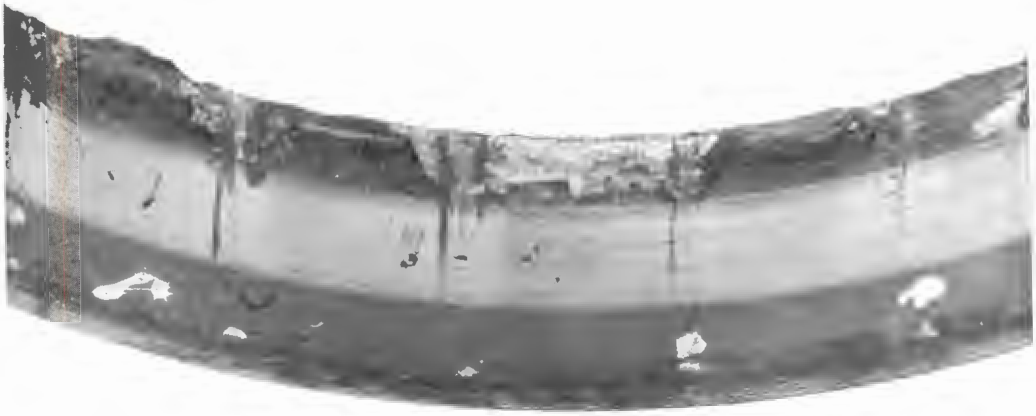

FIGURE 6. CLOSE-UP VIEW OF OUTER RACE

Figure 7 shows the carbonaceous type of deposits which accumulated within the bearing compartment. The additive-fuel jet can be seen at the 2 o'clock position. Its actual location during rig operation is at the 12 o'clock position. The jet was clear and was not obstructed during the test. This build-up of deposits would eventually interfere with bearing operation by restricting cage movement. However, by redesigning the chamber and using a high thermal stability fuel, it is felt that the deposits could be minimized. Also, relative to these deposits, it is to be noted that during the test run, no attempt was made to select an air/fuel ratio. While a quantity of air leaked past the shaft seal, and the additive-fuel lubricant flow was controlled to the jet, additional air was not supplied with the fuel.

The next step before proceeding with jet engine operation was to expose an aircraft engine bearing to the JP-5 tri-p-tolyl thiophosphate combination in the bearing rig. The J65 center main bearing was selected. This bearing is a 120-mm roller type. Races and rollers are M-10 steel. The cage or retainer is one piece, silicon-iron-bronze materials, with a 0.0005 inch silver plate all over. The cage rides on the outer race and calculations indicated that at 600°F there would be practically no clearance between the two members. Therefore, 0.020 inch was machined from the outside diameter of the silicon-iron-bronze cage. This also removed the silver plating from the rubbing surface of the cage. Satisfactory operation with the 120-mm engine bearing was obtained for 100 hours at the same conditions as the 100-mm Erdco bearing, except that the speed of the rig was reduced to 8300 rpm to simulate engine speed. The DN value was 1.0×10^6.

PHASE II - J65 ENGINE OPERATION

The second phase of bearing lubrication with additive fuel was turbojet engine operation. Figure 8 shows the test cell installation of the J65-W-4 engine which powers the A4D-1, the FJ-3 and FJ-4 aircraft. This engine was selected as the test vehicle after a study of various engine lubrication systems indicated that the once-through or "throw-away" system of the J65 could be utilized with the least number of modifications. The "overboard" vents are shown at the rear of the engine.

Figure 9 is a schematic diagram of the J65 lubrication system. In service this engine uses MIL-L-7808 lubricating oil. The front bearing is the thrust bearing and oil supplied to this bearing is recirculated back to the oil tank. The center or No. 2 bearing and the rear or No. 3 bearing are roller type and are the hot running bearings. Lubricating oil is metered to these bearings and, instead of being returned to the tank, is directed overboard. Fifth stage compressor bleed air is used for cooling the center and rear main bearings - two cooling tubes to the center, and four cooling tubes to the rear.

Figure 10 is a schematic diagram of the additive fuel lubrication system. The basic lubrication system has been modified to permit engine operation with either MIL-L-7808 or additive-fuel being supplied to the center and rear main bearings. By means of two solenoid valves, the MIL-L-7808 lubricant is shut off to the bearings and diverted back to the oil tank. The third solenoid valve is opened and additive-fuel lubricant flows to the bearings. The flow is controlled by the bypass valves. Cooling air supply to the bearings may be cut off by the six motorized valves. The front bearing system was not revised for this running.

Prior to installation, the No. 2 and No. 3 main bearing cages were modified by removing 0.010 inch from the outside diameter. Also, the oil jets to the bearings were reduced from 0.101 inch diameter to 0.031 inch diameter, in order to reduce the additive-fuel flow and still maintain a jet velocity. After completing a four-hour run-in and calibration with MIL-L-7808 lubricating oil being supplied to all bearings, the switch to additive fuel lubricant running was made.

Table 1 shows the J65-W-4 turbojet typical operating conditions with compressor cooling air to the bearings cut off, and JP-5 plus 1% tri-p-tolyl thiophosphate lubricant. Speed ranged from 8300-rpm at military to 3880 rpm at idle; thrust ranged from 7400 lb to 450 lb. The exhaust gas temperature was 1185 to 985°F. No. 2 bearing outer race temperature ranged from 475 to 150°F, No. 3 bearing outer race temperature 505 to 160°F, and No. 2-3 bearing compartment ambient 565 to 200°F. Except for brief periods of acceleration and deceleration these were the four power lever control settings used throughout the test. Figure 11 shows the effect of additive-fuel lubricant flow on the

FIGURE 7. BEARING CHAMBER DEPOSITS

FIGURE 8. J65-W-4 TURBOJET TEST CELL INSTALLATION

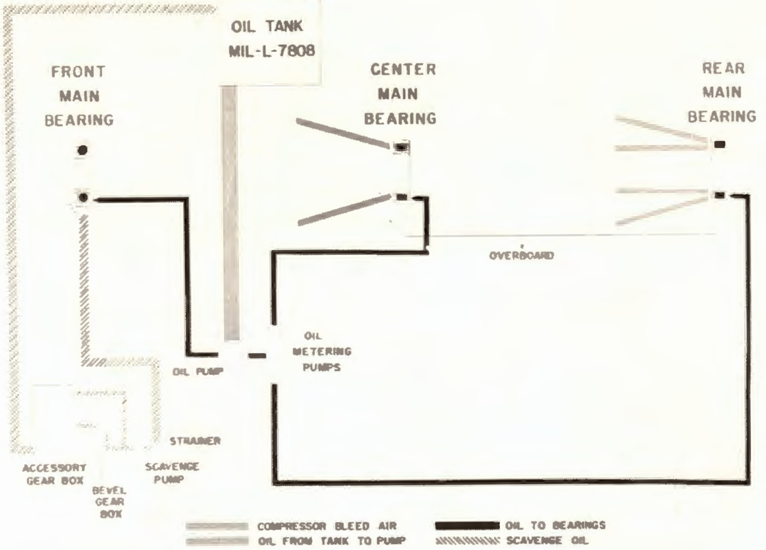

FIGURE 9. SCHEMATIC OF J65-W-4 LUBRICATION SYSTEM

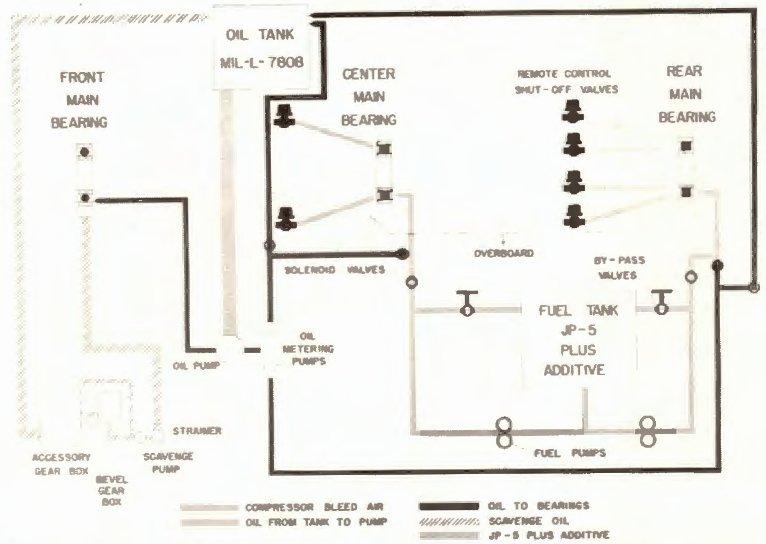

FIGURE 10. SCHEMATIC OF FUEL-ADDITIVE LUBRICATION SYSTEM

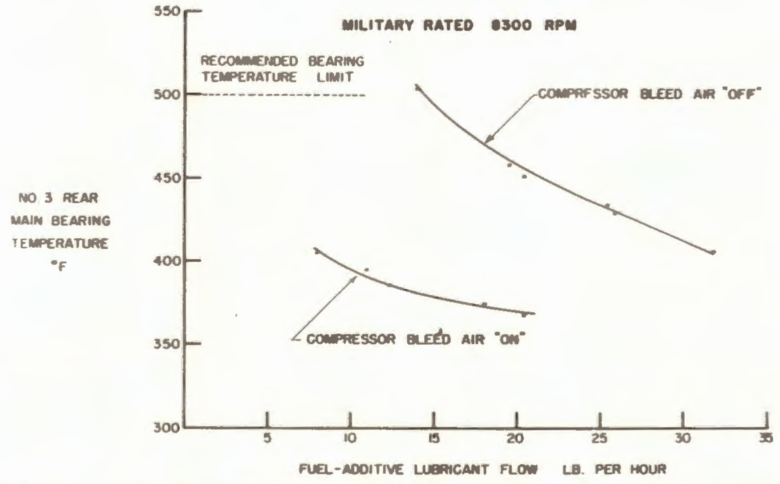

FIGURE 11. NO. 3 BEARING TEMPERATURE VS. ADDITIVE-FUEL LUBRICANT FLOW

No. 3 or rear bearing temperature. The upper curve represents the No. 3 bearing temperature when the additive fuel flow is varied from 14 pounds per hour to 33 pounds per hour, with the compressor bleed air to the bearing shut off. At 14 pounds per hour the outer race temperature was 505°F. This is 5°F over the recommended maximum operating temperature for the J65 engine. The high flow of 33 pounds per hour decreased the bearing temperature to 410°F. This is the approximate temperature for bearing operation in service when operating with MIL-L-7808 lubricating oil and compressor bleed air for cooling. The lower curve shows the bearing temperatures at various flow rates with the compressor bleed air "on". At the 410°F point the additive fuel lubricant flow was 8 pounds per hour or approximately 0.25 the flow required with the compressor bleed air "off".

After a total of 25 hours of engine operation on the additive fuel lubricant, with the majority of this time at the 500°F bearing temperature range, the center and rear main bearings were removed for inspection. Figure 12 is a close-up view of a section of the No. 2 bearing rollers, cage, and inner race as the assembly was removed from the engine. The dark areas on the rollers are carbon particles which were easily removed by a cotton cloth. The rollers were in good condition; no scoring or pitting was visible. Figure 13 is a close-up view of the No. 2 bearing inner race. The dark areas are small pieces of loose carbon and were wiped off with a cotton cloth. There were no scratches, scoring, or pitting. Figure 14 is a close-up view of the No. 2 bearing outer race. Part of the tracking area has a frosted appearance due to the additive which remained after shutdown. At the top of the race can be seen a build-up of carbon approximately 1/32 inch thick. The tracking area on this race is one-eighth wider than the rollers as a result of the rotor shaft moving axially due to temperature changes. There was no measurable wear on the bearing races. Figure 15 shows the silicon-iron-bronze cage which had very thin carbon deposits all over except at the rubbing surfaces on the outside diameter and in the roller pockets. The outside diameter of the bronze cage measures from 0.001 to 0.005 inch smaller than when installed for the test. As an "out of round" condition has now resulted probably due to heat, it is difficult to determine the amount of wear on the cage. Roller pocket wear is light.

Figure 16 is a close-up view of a section of the No. 3 bearing rollers, cage, and inner race assembled on the adapter as the unit was removed from the engine. Two rollers had very light scratches. No pitting was visible. Carbon deposits on the cage were thin and peeled readily. Figure 17 is a close-up of the No. 3 bearing inner race. The condition of this race is considered excellent. Figure 18 shows the No. 3 bearing outer race close up. Here again, and it is more apparent, we see the whitish residue left by the additive. The soak-back temperature of this race after shut down was 360°F. The tracking area has very light scratches, and is also approximately 1/8 inch wider than the rollers. The jet which supplied the JP-5 - tri-p-tolyl thiophosphate to this bearing can be seen at the cutout in the center of the bearing housing. This jet is actually below the running surface of the outer race and the additive-fuel does not impinge directly on the rollers and cage. Figure 19 shows the No. 3 bearing rollers and cage. The flaky type deposits on the cage are approximately 0.010 inch thick. The silver plating appears intact under these deposits. While the cage was exposed to the heat of the photographer's flood lamps, some of the deposits curled and dropped off. The cage measures 0.001 to 0.006 inch smaller than when installed and is out of round.

ADDITIONAL TESTS

Additional bearing rig tests with the Erdco 100-mm bearing have been:

(1) A run at 10,000 rpm, 500 lb radial load, and 600°F outer race temperature, using JP-5 fuel plus 1% tricresyl phosphorothionate as a lubricant was satisfactory for 85 hours. The test was terminated at this point due to having exhausted the 2000 gram sample. The additive sample was in a liquid form when received and was soluble in JP-5 fuel. The tricresyl phosphorothionate was made from commercial mixed m, p-cresol, and has the same chemical formula as the tri-p-tolyl thiophosphate.

(2) A run which is continuing, has a 100-mm test bearing operating at 700°F for 56 hours using JP-5 plus 1% tri-p-tolyl thiophosphate.

FIGURE 12. NO. 2 BEARING ROLLERS, CAGE AND INNER RACE

FIGURE 13. NO. 2 BEARING INNER RACE

FIGURE 14. NO. 2 BEARING OUTER RACE

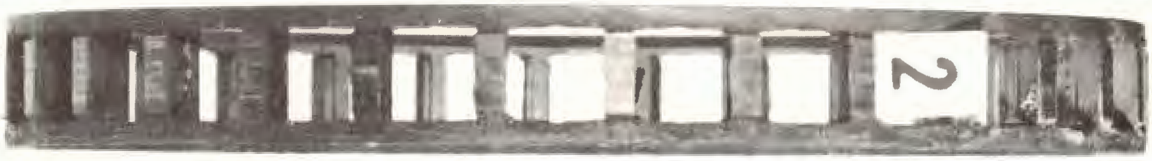

FIGURE 15. NO. 2 BEARING CAGE

FIGURE 16. NO. 3 BEARING ROLLERS, CAGE AND INNER RACE

FIGURE 17. NO. 3 BEARING INNER RACE

FIGURE 18. NO. 3 BEARING OUTER RACE

FIGURE 19. NO. 3 BEARING ROLLERS AND CAGE

CONCLUSIONS

1. Results of the bearing rig tests using JP-5 plus 1% tri-p-tolyl thiophosphate have shown good correlation with engine operation.

2. The air/fuel ratio was not selected during engine operation with the additive-fuel lubricant. Major engineering changes would have to be incorporated in the J65 engine to exclude the air which leaks past the seals during running. With the compressor bleed air shut off to the center and rear main bearings, the bearing compartment had a pressure of 2 psi gage.

3. Additive and JP-5 fuel combinations based on the total amount of sulfur contained therein were not evaluated at this time.

4. The work to date has demonstrated that the additive-fuel lubricant method is feasible for jet engine application. While no tests have been conducted to study bearing life, the 25-hour engine test tends to show that cage wear will probably be the limiting factor in practical applications.

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4. Lockwood, A. L., "High-Temperature Bearing Lubrication with Additive Fuels," AEL Report No. 1487.