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LUBRICANTS FOR HIGH-TEMPERATURE 20-MILLIMETER-

BORE BALL BEARINGS

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INVESTIGATION OF TEMPERATURE LIMITATION OF VARIOUS LUBRICANTS

FOR HIGH-TEMPERATURE 20-MILLIMETER-BORE BALL BEARINGS

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SUMMARY

Lubrication studies of bearings lubricated with liquids (introduced in droplet form) and solids (introduced in an air stream) were made in a bearing test rig under conditions of minimum lubricant flow, that is, very little cooling by the lubricant. The following six liquid lubricants, consisting of two petroleums and four synthetics, were investigated: The petroleums were MIL-O-6081A grade 1010 oil and MIL-F-5624B grade JP-4 jet-engine fuel; the synthetics were di(2-ethylhexyl)sebacate plus additives, dioctyl isooctene phosphonate, tetrakis(2-ethylhexyl)silicate plus an additive, and a silicone-diester blend. Two solids, molybdenum disulfide and graphite, were also investigated.

The investigation was conducted with 20-millimeter-bore ball bearings of 18-4-1 tool steel. Most of the bearing cages were two-piece stampings of silver-plated beryllium copper riveted together. Others were two-piece riveted bearing cages machined from cast Inconel.

Under the conditions of these experiments the solid - air-mist lubricants were better high-temperature lubricants than were the liquids. All tests of solid - air-mist lubricants were run to completion from 100° to 1000° F. Graphite was a better lubricant than molybdenum disulfide because it provided effective lubrication, with bearings equipped with either a beryllium copper or an Inconel cage, throughout the temperature range (100° to 1000° F). Molybdenum disulfide provided effective lubrication only to 850° F with a bearing equipped with an Inconel cage.

A blend of a silicone and a diester was the best high-temperature liquid lubricant tested. Effective lubrication was provided to 700° F, and no failure occurred at 850° F despite high friction torque.

Although bearings with beryllium copper cages operated at lower friction torques than those with Inconel cages, this may have been caused by differences in cage design. Although only low stresses were imposed on the cages, several of the beryllium copper cages were fractured. Results with cast Inconel cages were considered promising enough to justify trials in full-scale-engine bearing tests.

Experiments with dried graphite and extremely dry air as the carrier showed effective lubrication to 1000° F, although friction-torque values were higher than those obtained with undried graphite.

Results obtained with JP-4 fuel as a lubricant were unusual in that one of the test bearings ran to 700° F with low friction torque despite the fact that a cage fracture (discovered at shutdown) had occurred during the test. In a second test with JP-4 fuel, high friction torque and a cage fracture resulted at 550° F.

Within their effective operating ranges, friction-torque values were similar for the liquid and the solid lubricants.

INTRODUCTION

Operating temperatures of high-speed rolling-contact bearings are at present limited mainly by the lubricants and to a lesser extent by the bearing materials (refs. 1 and 2). Metallurgical aspects of rolling-contact bearings, with particular reference to their use in air-craft gas turbines for high-temperature application, are discussed in reference 3. The present-day liquid lubricants have a maximum tempera-ture limit beyond which their performance characteristics begin to de-teriorate rapidly (refs. 4 and 5) through processes such as evapor-ation, thermal decomposition, and oxidation. Although known liquids can still be improved somewhat and the environment of the bearings can be altered, bearings will still have to be operated at temperatures in ex-cess of the temperature limits of present and of immediately forseeable lubricants.

Oil - air-mist and circulating oil-jet lubrication are employed at present in turbojet engines. Only a small fraction of the oil supplied to the bearing is needed as a lubricant, since the bulk of the oil is used to carry away the heat generated by the bearing and the heat flow-ing to the bearing from the engine. Thus, the bearing is cooled to a low-temperature level that does not cause excessive evaporation or chem-ical breakdown of the oil. With high-temperature operation of future turbojet engines (ref. 1), attempts to keep bearing temperatures at their present levels would impose a very difficult burden on the avail-able cooling capacity. In order to reduce the oil-system heat load, bearings must be allowed to operate at higher temperatures. This high-temperature operation can be attained only if lubricants with better high-temperature stability can be developed.

This investigation is a continuation of the work reported in refer-ence 6, which was a preliminary investigation of molybdenum disulfide MoS_2 as a bearing lubricant at high temperatures and low speeds and at high speeds and low temperatures. Ball bearings of 1-inch bore were

operated with MoS_2 - air-mist lubrication to temperatures of 1000° F at low speeds, and 75-millimeter-bore roller bearings were operated to DN values (product of bearing bore in mm and shaft speed in rpm) up to 0.975×10^6 with MoS_2 syrup-bonded coatings and MoS_2 - air-mist lubrication.

This investigation was conducted at the NACA Lewis laboratory to determine the temperature limitation of various liquid and solid lubricants for high-temperature operation. Test bearings were size 204 (20-mm bore, 14-mm width, and 47-mm outside diameter) ball bearings. Races and balls were made of 18-4-1 tool steel. Thirteen test bearings were equipped with two-piece, stamped and riveted silver-plated beryllium copper cages; four were equipped with two-piece, machined and riveted cast Inconel cages, three of which were precoated with a nickel oxide film.

Low bearing friction torque was used as the criterion of effective lubrication.

APPARATUS

Bearing Rig

The bearing rig (fig. 1) used for this investigation was constructed around an ordinary floor-type drill press. In addition to the drill press, the rig consisted of a resistance furnace, a spindle, and a special test-bearing housing assembly to permit measurement of bearing friction torque. Load was applied by dead weights acting on the spindle through a lever system. Modifications made to the drill press enabled accurate axial loading of the test bearing and measurement of the test-bearing inner-race temperature.

The test bearing was mounted on a short shaft, which was fitted into the drill-press spindle through a tapered press fit. The outer race of the bearing was mounted in the special Inconel bearing housing assembly in the furnace cavity; this assembly is described fully in reference 7 and is shown in figure 1. It is essentially an externally pressurized, parallel-surface nonrotating air-thrust bearing. The air-thrust bearing provided an essentially frictionless support for the test bearing in order that friction torque could be measured accurately at all bearing temperatures. Details of the externally pressurized air-thrust bearing are shown in figure 1(a).

The furnace (fig. 1(a)) consisted of an Inconel cylinder heated by coils of Nichrome wire wound around the cylinder. The furnace was equipped with an automatic temperature control.

Friction-Torque Measurement

Bearing friction torque was measured by means of a calibrated force-measuring transducer, which restrained the air-thrust bearing from moving. In the absence of rotative motion the air-thrust bearing will introduce no friction torque, so that the torque measured will be that developed by the test bearing alone. Friction torque was recorded by means of a photoelectric potentiometer recorder with an accuracy of ±3 percent.

Temperature Measurement

Test-bearing outer-race temperature was obtained by the use of an iron-constantan thermocouple located in the test-bearing housing. An additional thermocouple for the temperature-control instrument was also located in the test-bearing housing. In order to minimize friction-torque effects from the thermocouple leads leaving the housing, a special 3-foot section of very fine-gage wire was hung vertically.

Test-bearing inner-race temperature was measured by an iron-constantan thermocouple pressed against the bore of the inner race at the axial midpoint of the bearing. The thermocouple wires were brought out through a hole in the center of the drill-press spindle. The thermocouple electromotive force was transmitted from the rotating spindle by means of small slip rings located on the end of the spindle (ref. 8).

Test Bearings

The test bearings used for this investigation were size 204 (20-mm bore, 14-mm width, and 47-mm outside diameter) ball bearings made of 18-4-1 high-speed tool steel (18 percent tungsten, 4 percent vanadium, and 1 percent chromium). Test bearings were constructed with a nominal 0.0004-inch diametral clearance to ABEC - 3 tolerances. Two types of cages were used in the test bearings. The first type was a two-piece, stamped and riveted ball-riding cage made of silver-plated beryllium copper. The second type was a two-piece, machined and riveted inner-race-riding cage made of cast Inconel. Cast Inconel was used as a cage material because of the desirable high-temperature properties revealed in basic friction and wear tests (ref. 9). Three of the Inconel cages were treated with a bath of molten sodium hydroxide NaOH at approximately 750° F for 3 hours to produce a nickel oxide coating with good frictional properties. Schematic drawings of the test bearings are shown in figure 2.

Lubricants

The liquid lubricants were divided into petroleums and synthetics. The petroleums included MIL-O-6081A grade 1010 oil and MIL-F-5624B grade JP-4 jet-engine fuel. The synthetic oils were as follows:

(1) A compounded diester of di(2-ethylhexyl)sebacate with 0.5 percent phenothiazine as an oxidation inhibitor, 5 percent tricresyl phosphate as an antiwear additive, about 4 percent methacrylate polymer viscosity-index improver, and 0.05 percent antifoam silicone oil

(2) A phosphonate (dioctyl isooctene phosphonate)

(3) A silicate (tetrakis(2-ethylhexyl)silicate) with 1 percent phenyl-α-naphthylamine as an oxidation inhibitor

(4) A silicone-diester blend SD-17 of 1/3 di(2-ethylhexyl)sebacate plus 2/3 methylphenyl polysiloxane (100 centistokes at 77° F) plus 0.5 percent phenothiazine as an oxidation inhibitor

The liquid lubricants and some of their properties are listed in table I.

The solid lubricants were MoS_2 and graphite.

Lubrication Systems

Liquid lubricants. - For the liquid lubricants a small metering pump driven by a variable-speed motor was used. In order to reduce the lubricant flow to the required few drops per minute, a 40-inch length of 0.020-inch inside-diameter capillary tube was used in conjunction with a needle-type bypass valve. In order to reduce the explosion hazard when JP-4 fuel was used, a 100-cubic-centimeter syringe was substituted for the metering pump and motor. The weight of the syringe plunger was used to force the JP-4 liquid through the capillary tube to the bearing.

Solid lubricants. - For solid - air-mist lubrication the system consisted of a low-pressure air supply, a pressure-regulating valve, a conventional float-type rotameter, a combination air filter and dehumidifier, two 4-ounce bottles, a vibrator for the bottles, and a section of 3/16-inch stainless steel tubing which carried the solid - air-mist lubricant to the vicinity of the bearing.

The air was filtered through a 2-micron filter and dried (maximum relative humidity, 70 percent). For special tests requiring dry air, an activated alumina adsorption air drier was used. For these tests the dew point of the air was lower than -60° F. Figure 3 shows a

schematic diagram of the solid-particle - air-mist lubrication arrange-
ment. Pressurized air was introduced into the upstream bottle to agitate
the lubricant and carry it downstream. The second bottle served as a
trap for excessively large particles and as a visual gage to determine
qualitatively the lubricant flow rate. Both bottles were vibrated to
keep the powder mobile.

PROCEDURE

All runs were conducted at a constant speed of 2500 rpm (the limita-
tion of the test rig) and a 110-pound thrust load over a range of bearing
outer-race temperatures from 100° to 1000° F or failure, whichever
occurred first. Test-bearing outer-race temperatures were raised in
increments of 150° F. Test bearings were operated continuously during
the time required (about 1 to $1\frac{1}{4}$ hr) to reach each temperature level and
continued at each designated temperature for 2 hours. Because the max-
imum total running time per bearing was 20 hours or more, the rig was
shut down at the end of each day and restarted the next day.

It was found that, when solid - air-mist lubrication was employed,
the bearing was very sensitive to the amount of lubricant flow. An
insufficient flow produced the symptoms of an incipient failure, and an
excessive flow resulted in a grating sound and an increase in friction
torque. The flow of solid - air-mist lubricant was frequently adjusted
to produce minimum friction torque and noise level. The lubricant flow
rate was 15 to 55 drops per minute (approximately 2×10^{-4} to 1×10^{-3}
lb/min for liquids and 2×10^{-5} to 15×10^{-5} lb/min for solids). The air
flow required to carry the solid particles to the bearing was approxi-
mately 0.053 to 0.23 cubic foot per minute.

Failure was characterized by high (exceeding 0.5 in.-lb) and un-
stable bearing friction torque and noisy operation of the test bearing.
In addition, failure due to cage breakdown could be detected by visual
inspection during shutdown if other means failed to indicate the trouble.

RESULTS AND DISCUSSION

The results of the experimental investigation in which 17 bearings
were tested are summarized in table II and in figures 4 to 8. Figures
8(a) and (b) are photographs of new test bearings illustrating the two
types of cages used in these tests; figures 8(c) to (r) are photographs
of bearings after testing.

Bearings with Silver-Plated Beryllium Copper Cages

Dry operation (test 1). - In test 1 no lubricant was supplied to the test bearing. Failure occurred after 3 hours and 6 minutes of operation. Bearing friction torque (fig. 4) first increased momentarily after 1 hour and 24 minutes of operation. After 2 hours and 55 minutes the bearing began to fail, and about 10 minutes later friction torque increased from 0.4 to 4.75 inch-pounds. A photograph of bearing 1 after the tests is shown in figure 8(c). The cage was broken in one place and the inner race, balls, and cage were slightly discolored (a light straw color) from frictional heat. At the time of failure the inner-race temperature was approximately 540° F (290° F higher than that of the outer race). This temperature differential undoubtedly produced a high load between the bearing balls and races because of the loss of diametral clearance and could have been responsible for the cage breakage.

Petroleum liquids (tests 2 and 3). - In test 2 the lubricant was MIL-O-6081A grade 1010 oil, which is currently used in several turbojet engines. Friction-torque values, shown in figure 5(a), indicate that failure began at a temperature of 550° F and quickly progressed to a total failure in going from 550° to 700° F. Friction torque reached 5 inch-pounds before shutdown. The total running time was 14.1 hours. Failure was evidenced by cage breakage in several positions (fig. 8(d)). The bearing was fairly clean with a very slight deposit of varnish on the parts.

Tests 3a and 3b were conducted using MIL-F-5624B grade JP-4 jet-engine fuel as the lubricant (fig. 5(b)). In the figure the solid curve gives the average friction torque and the broken line the extreme values of friction torque. Friction-torque values were fairly low at temperatures to and including 700° F for test 3a. Failure of the bearing, evidenced by breakage of the cage at one location, was detected by visual inspection at the end of the 2-hour run at 700° F (fig. 8(e)). Test 3b showed a friction trend similar to that of test 3a at temperatures up to 400° F, but the bearing failed in going to 550° F with friction torque reaching 2.64 inch-pounds. The bearing used in test 3b sustained a multiple cage fracture. The total running time with JP-4 fuel was 16 hours for test 3a and 9.8 hours for test 3b. The bearings were relatively clean but slightly darkened.

Synthetic oils (tests 4 to 7). - Tests 4a and 4b were conducted with a compounded diester, which approaches the requirements of military specification MIL-L-7808, as a lubricant. The results of these tests are shown in figure 5(c), and a photograph of the bearing after the tests is shown in figure 8(f). In both tests friction torque was low at temperatures to and including 700° F. Test 4b was terminated at 700° F because of heater failure; no bearing failure occurred. In test 4a friction torque rose rapidly when the bearing was being heated from 700° to 850° F. Failure occurred in this temperature range; at shutdown, friction torque had reached approximately 3.44 inch-pounds. The cage was

broken and several sections were missing. The bearing was relatively clean but slightly darkened. The total running time was 15.15 hours for test 4a and 16 hours for test 4b.

In test 5 the lubricant was a phosphonate. The maximum temperature at which the bearing operated satisfactorily was 450° F. Friction torque increased rapidly to 3.5 inch-pounds when the bearing was being heated from 400° to 550° F (fig. 5(d)). Although no mechanical failure occurred, the test bearing was almost completely covered with a heavy carbonaceous deposit (fig. 8(g)). The total running time for test 5 was 8.5 hours.

In test 6 the lubricant was a silicate. This lubricant was slightly better than the phosphonate in that it allowed bearing operation at 550° F for 2 hours with high and unstable friction torque, ranging from 0.26 to 1.04 inch-pounds (fig. 5(e)). At temperatures slightly above 550° F, friction torque increased rapidly and the test was stopped before severe damage could occur to the test bearing. The friction torque was 1.84 inch-pounds at shutdown. Again, as in test 5 with the phosphonate as the lubricant, there was no mechanical failure; but, in contrast to the heavy deposits with the phosphonate, there was only a slight brown deposit with the silicate (fig. 8(h)). The total running time was 11.3 hours.

Test 7 was conducted with the silicone-diester blend as the lubricant. Friction torque was low and stable throughout the range of temperatures to 850° F (fig. 5(f)). At 850° F, however, friction torque varied from 0.23 to 1.46 inch-pounds. The bearing completed the 2-hour run at 850° F despite the high and unstable friction torque. Since a slight increase in temperature above 850° F resulted in further increases in friction torque, the test was terminated. The cage had not broken. Figure 8(i) shows the heavy deposit on the lubricant inlet side of the bearing. The lubricant outlet side of the bearing (fig. 8(j)) shows less deposit, indicating that the lubricant decomposed before reaching this area. The total running time was 16.25 hours.

Solid lubricants (tests 8 to 10). - Test 8 had MoS_2 - air mist as the lubricant. Although friction torque was fairly high and unsteady at the 100° F temperature level (fig. 5(g)), it was steady and low at 250°, 400°, and 550° F. At 700° F, friction torque again became unsteady and remained so until the end of the test at 1000° F. The maximum friction torque at shutdown was 3.64 inch-pounds. The total running time was 19.05 hours. Figures 8(k) and (l) show views of both sides of the bearing after testing. Figure 8(k) shows the lubricant inlet side of the bearing, where extensive damage to the cage is clearly evident. The opposite side of the cage is still intact (fig. 8(l)), although it too shows evidence of damage. At temperatures above 750° F in the presence of oxygen, MoS_2 begins to oxidize at a rate that increases with increasing temperature (ref. 10). The oxidation products include molybdenum

trioxide MoO_3 (an abrasive material) and sulfur dioxide SO_2, which could readily react with the cage material (both the beryllium copper and the silver plate). The extensive cage damage that occurred in these tests could have been caused by corrosion.

Tests 9a and 9b were run with graphite - air mist as the lubricant. Friction torque in general decreased with temperature (fig. 5(h)) throughout the temperature range to 1000° F. At 1000° F friction torque was very low for both tests, ranging from 0.05 to 0.1 inch-pound for test 9a. The bearings were clean except that they were covered with a thin film of graphite powder (fig. 8(m)). No corrosion was in evidence and all bearing components showed little evidence of wear or damage of any kind. The total running time was 18.65 hours for bearing 9a and 18.7 hours for bearing 9b.

In test 10, dried graphite was the lubricant. Specially dried air was used in place of ordinary supply air to carry the particles of dried graphite to the bearing. The effectiveness of graphite as a lubricant has been shown to depend on the presence of moisture or certain gases (ref. 11). As can be seen from the curve for friction torque (fig. 5(i)), graphite, in the absence of moisture, was not quite as effective a lubricant as when moisture was available. Although friction-torque values for the dried graphite were higher and more unsteady than were those for the nondried graphite, the test was completed. In the temperature range of 700° to 1000° F, friction torque was considerably reduced. This reduction may have been caused by seepage of minute quantities of moisture into the lubricant despite the extensive precautions taken or by increased effectiveness of gases such as oxygen. The bearing after the test (fig. 8(n)) was comparable in appearance to the bearing used in tests 9a and 9b, rotated freely, and was unbroken. The total running time was 18.5 hours.

Bearings with Cast Inconel Cages

Solid lubricants (tests 11 to 13). - The bearing used in test 11 was equipped with an oxide-coated cast Inconel cage and was lubricated by MoS_2 - air mist. Figure 6(a) shows the results of this test. Friction torque decreased from its initial value to temperatures of 400° F and thereafter increased steadily at temperatures to 1000° F. Friction torque was fairly stable to and including 850° F. Above 850° F, friction torque became more unstable but was still more stable and lower in magnitude than that for a bearing equipped with a silver-plated beryllium copper cage (test 8, fig. 5(g)). On completion of test 11, all bearing components were found intact. A small amount of light yellowish-white deposit was observed on the bearing, mainly at the cage-locating surface (fig. 8(o)). The entire cage had a gray vapor-blasted appearance. The bearing turned roughly and tightly. The total running time was 20.9 hours.

In test 12 the lubricant was graphite - air mist, and the cage was constructed of oxide-coated cast Inconel. The purpose of this test was to compare cast Inconel and silver-plated beryllium copper as high-temperature cage materials. The test was run to completion although friction torque was quite high and unstable throughout most of the temperature range (fig. 6(b)), reaching its maximum value at 850° F. Friction torque was very erratic at 850° F, but it steadied and was smooth at 1000° F. This change may have been caused by an increased rate of formation of nickel oxide on the surface of the cage at high temperatures, as indicated by unpublished results. Similar results were not obtained with MoS_2, probably because it forms an abrasive decomposition product above 750° F. With graphite at 1000° F, friction torque ranged from 0.2 to 0.36 inch-pound, with an average value of 0.33 inch-pound (fig. 6(b)). It can be seen that these values of friction torque are higher than those for the bearings with the silver-plated beryllium copper cage (fig. 5(h)). Differences not only in cage material but also in cage design undoubtedly are responsible for the variation in friction torque. The bearing components upon completion of test 12 were intact and were free to rotate easily (fig. 8(p)). The total running time was 19.6 hours.

In test 13 the lubricant was graphite - air mist. The cage material was untreated cast Inconel; thus, no prepared oxide film was present. Values of friction torque for this test (fig. 6(c)) were, in general, comparable with those for the other graphite tests throughout the temperature range from 100° to 1000° F. A reduction in friction torque below that for the oxide-coated cage may be noted in the range of temperatures from 700° to 850° F. Bearing operation was considerably smoother with the uncoated cage, and at the conclusion of the test all bearing components were intact (fig. 8(q)) and the bearing rotated freely. The total running time was 18.1 hours.

Silicone-diester blend (test 14). - Test 14 was run with the silicone-diester blend as the lubricant and with the cage oxide-coated. This test was run at 550° F for 39.25 hours; during this time friction torque was low and steady. The test was then run at 700° F for 2 hours before friction torque became unstable and increased to a value of 1.5 inch-pounds (fig. 7). After shutdown it was found that the bearing was heavily coated with a rubbery film (fig. 8(r)). The bearing components were intact.

Analysis of Experimental Results

Although the results reported herein were obtained at low DN values with relatively small bearings, the trends indicated are believed to be valuable as pilot tests which serve to decrease full-scale-engine bearing testing.

Comparison of results with liquid and solid lubricants. - Solid
lubricants were found to be superior to liquid lubricants at high tem-
peratures. Both graphite and MoS_2 gave better results than the best
liquid lubricant (silicone-diester blend). Graphite provided effective
lubrication at temperatures to 1000° F in all four tests in which it was
used. Molybdenum disulfide - air mist provided effective lubrication
at temperatures to 850° F and permitted bearing operation at 1000° F.
The difference in results with graphite and MoS_2 is believed to be due
to the properties of the decomposition products of these lubricants.
Graphite oxidizes to form a gas; MoS_2, however, oxidizes in the presence
of air at high temperatures, forming an abrasive product (ref. 10). How-
ever, MoS_2 is very stable in the absence of oxygen at high temperatures
(ref. 12). Although friction-torque values for the dried graphite were
initially higher than those for the undried graphite, they became com-
parable at higher temperatures.

Among the liquid lubricants tested, the silicone-diester blend
allowed the bearing to operate to the highest temperature (850° F) under
the conditions of these tests. Friction torque was stable and low at
all temperature levels except at 850° F. The next best liquid lubricant
was also a synthetic oil, di(2-ethylhexyl)sebacate plus additives. This
oil permitted operation to 700° F but proved ineffective at higher tem-
peratures. Although one of the test bearings lubricated with JP-4 fuel
ran to 700° F with low friction torque, the lubrication was not effective
since the cage was found to be broken when the rig was shut down. An-
other bearing lubricated with JP-4 fuel ran at 400° F but failed when
going to a higher temperature. None of the remaining liquid lubricants
(grade 1010 oil, the phosphonate, or the silicate) provided effective
lubrication above 550° F.

Comparison of cage materials. - The relative merits of the two cage
materials tested are difficult to evaluate because this type of test is
not as severe a test of the cage as a full-scale-engine bearing test at
high DN values. Since similar tests were run with the silver-plated
beryllium copper and the cast Inconel cages using MoS_2 and graphite as
lubricants, the cages are compared on the basis of these tests.

Of the two cage materials, Inconel showed slightly higher friction-
torque values at temperatures to 700° F when lubricated with MoS_2. Above
700° F, however, the beryllium copper cage showed the higher friction-
torque values. When the bearings were lubricated with graphite, the
average friction torques with both cage materials were comparable. How-
ever, for the cast Inconel cage, friction torque was more erratic and
slightly higher than for the beryllium copper cage (figs. 5(h) and 6(b)).

The magnitudes of friction-torque values in the regions of satis-
factory lubrication were similar for both liquid and solid lubricants.

For instance, grade 1010 oil produced friction torques between 0.1 and 0.2 inch-pound (fig. 5(a)); MoS_2 operated at 0.11 inch-pound (fig. 5(g)); and graphite operated between average values of 0.06 and 0.29 inch-pound (fig. 5(h)).

SUMMARY OF RESULTS

The following results were obtained with 20-millimeter-bore, tool-steel ball bearings, equipped with either two-piece, stamped and riveted silver-plated beryllium copper cages or with two-piece, machined and riveted cast Inconel cages and lubricated with various solid and liquid lubricants at bearing temperatures from 100° to 1000° F, a bearing speed of 2500 rpm, and a thrust load of 110 pounds:

1. The solid lubricants tested (graphite and molybdenum disulfide) proved to be better high-temperature lubricants than the liquids tested (several synthetics and petroleums). The solid lubricants (introduced as a solid - air mist) provided effective lubrication (as evidenced by low friction torque) up to 1000° F, whereas the best liquids (introduced in droplet form) provided effective lubrication to 700° F.

2. Of the two solids tested, graphite lubricated effectively at 1000° F with bearings equipped with either a beryllium copper cage or an Inconel cage, while molybdenum disulfide lubricated effectively to 850° F with a bearing equipped with an Inconel cage and allowed bearing operation at 1000° F without failure. Bearings lubricated with graphite were clean and showed little evidence of wear; bearings lubricated with molybdenum disulfide were quite contaminated and, where the cage material was beryllium copper, showed evidence of extensive wear (probably corrosion).

3. Among the liquid lubricants tested, a blend of a silicone and a diester allowed bearing operation to 850° F. Effective lubrication was provided at 700° F, and no failure occurred at 850° F despite high friction torque.

4. Several beryllium copper cages failed by fracturing. The Inconel cages were not fractured, and their performance was considered promising enough to justify trials in full-scale-engine bearing tests.

5. A test run with dried graphite and dried air (dew point, <-60° F) produced friction-torque values higher than those obtained with undried graphite. However, effective lubrication was obtained to 1000° F, either because of adsorbed gases or moisture seepage into the system.

6. Results obtained with JP-4 fuel (tested in two bearings) were unusual in that one of the test bearings ran to 700° F with low friction torque despite the fact that a cage fracture (discovered at shutdown) had

occurred during the test. The second bearing ran at 400° F and failed when going to a higher temperature level.

7. Friction-torque values were similar for both the liquid and solid lubricants within their respective effective operating ranges.

Lewis Flight Propulsion Laboratory
     National Advisory Committee for Aeronautics
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11. Savage, R. H.: Graphite Lubrication. Jour. Appl. Phys., vol. 19,
    no. 1, Jan. 1948, pp. 1-10.

12. Hodgman, Charles D.: Handbook of Chemistry and Physics. Thirty-
    fifth ed., Chemical Rubber Pub. Co., 1953-1954, p. 552.

TABLE I. - PROPERTIES OF LIQUID LUBRICANTS

Liquid	Viscosity, centistokes, at -				A.S.T.M. pour point, °F	C.O.C. flash point, °F	C.O.C. fire point, °F	S.I.T.,[a] °F
	-65° F	-40° F	100° F	210° F				
Petroleum:								
MIL-O-6081A grade 1010[b]	40,000	----	9.95	2.47	< -70	300	----	500
MIL-F-5624B grade JP-4 jet-engine fuel	5	----	.86	.51	----	---	----	484
Diester:								
Di(2-ethylhexyl)sebacate + additives[c,d,e,f]	16,000	2700	20.8	5.3	< -75	450	475	---
Phosphonate:								
Dioctyl isooctene phosphonate[b]	------	[g]9003	12.22	2.77	-90	---	---	---
Silicate:								
Tetrakis(2-ethylhexyl)silicate + oxidation inhibitor[f,h]	1,400	260	6.8	2.4	< -100	395	450	---
Silicone-diester blend, SD-17: $\frac{1}{3}$ di(2-ethylhexyl)sebacate[b,e,i] + $\frac{2}{3}$ methylphenyl polysiloxane (100 centistokes at 77° F)	3,750	1050	42	14.2	< -80	450	500	---

[a]Spontaneous ignition temperature.

[b]Measured values.

[c]4 Percent methacrylate polymer.

[d]5 Percent tricresyl phosphate.

[e]0.5 Percent phenothiazine.

[f]Manufacturer's data.

[g]At -50° F.

[h]Phenyl-α-naphthylamine (1 percent).

[i]Parts by volume.

TABLE II. — EFFECT OF TEMPERATURE ON BEARING LUBRICATION

[Speed, 2500 rpm; thrust load, 110 lb. Lubrication failure was generally presumed when friction torque exceeded 0.5 in.-lb]

| Test	Bearing construction	Lubricant type	Lubricant flow rate, lb/min	Lubrication method	Air-flow rate, cu ft/min	Maximum successful operating temperature, °F			Bearing torque at maximum successful temperature, in.-lb		Total running time, hr	Remarks
						Ambient	Inner race	Outer race	Average	Range		
1	Stamped and riveted silver-plated beryllium copper cage	Dry	--------	------	0	115	160	130	0.45	0.20 to 1.30	3.1	Failure; cage broken. Bearing friction torque at failure was just below 5 in.-lb. Inner race, balls, and cage slightly discolored.
2	Stamped and riveted silver-plated beryllium copper cage	MIL-O-6081A grade 1010 petroleum oil	0.0003 to 0.001 (15 to 55 drops/min)	Fluid drop	0	656	545	538	0.20	0.11 to 0.39	14.1	Failure; cage broken in several places. Bearing friction torque at failure was 5 in.-lb. Bearing relatively clean.
3a	Stamped and riveted silver-plated beryllium copper cage	MIL-F-5624B grade JP-4 jet-engine fuel	0.0002 to 0.0003 (20 to 24 drops/min)	Fluid drop	0	713	664	697	0.20	0.04 to 0.56	16	Failure; cage broken in several places. Bearing friction torque was low despite failure. Bearing relatively clean but darkened.
3b	Stamped and riveted silver-plated beryllium copper cage	MIL-F-5624B grade JP-4 jet-engine fuel	0.0002 to 0.0003 (20 to 24 drops/min)	Fluid drop	0	444	388	400	0.15	0.08 to 0.20	9.8	Failure; cage broken in several places. Bearing friction torque at failure was 2.64 in.-lb. Bearing clean.
4a	Stamped and riveted silver-plated beryllium copper cage	Di(2-ethylhexyl) sebacate + additives[a,b,c] (PRL 3161)	0.001 (55 drops/min)	Fluid drop	0	810	---	710	0.04	0.04 to 0.19	15.15	Failure; cage broken in several places. Bearing friction torque at failure was 3.44 in.-lb. Bearing clean but darkened.
4b	Stamped and riveted silver-plated beryllium copper cage	Di(2-ethylhexyl) sebacate + additives[a,b,c] (PRL 3161)	0.0003 to 0.001 (15 to 55 drops/min)	Fluid drop	0	788	697	713	0.05	0.025 to 0.07	16	No failure; test terminated at end of 700° F period because of furnace heater failure.
5	Stamped and riveted silver-plated beryllium copper cage	Dioctyl iso-octene phosphonate	0.0003 (15 drops/min)	Fluid drop	0	440	402	418	0.11	0.05 to 0.13	8.5	No failure; cage not broken. Bearing friction torque was 3.5 in.-lb at shutdown. Heavy carbonaceous deposit in bearing.
6	Stamped and riveted silver-plated beryllium copper cage	Tetrakis (2-ethylhexyl) silicate + oxidation inhibitor[d]	0.0003 (15 drops/min)	Fluid drop	0	584	576	548	0.60	0.26 to 1.04	11.3	No failure; cage not broken. Bearing friction torque was 1.84 in.-lb at shutdown. Slight deposit in bearing.
7	Stamped and riveted silver-plated beryllium copper cage	Silicone-diester blend[e]	0.0003 (15 drops/min)	Fluid drop	0	905	---	875	----	0.23 to 1.46	16.25	No failure; cage not broken. Bearing friction torque was low and steady to above 700° F. It was 1.46 in.-lb at shutdown. Heavy salt-like silica deposit on bearing.
8	Stamped and riveted silver-plated beryllium copper cage	MoS₂	0.00002 to 0.00015	Air mist	0.053 to 0.23	1062	938	1001	2.96	1.30 to 2.96	19.05	Failure; cage corroded and broken on lubricant supply side of bearing. Bearing friction torque very high at last several hours of test. Heavy deposits on bearing.
9a	Stamped and riveted silver-plated beryllium copper cage	Synthetic graphite	0.00002 to 0.00015	Air mist	0.053 to 0.23	1023	882	1000	0.08	0.05 to 0.10	18.65	No failure; cage not broken. Bearing friction torque only 0.08 in.-lb at 1000° F and was steady. Bearing was clean and free with slight film of graphite on bearing.
9b	Stamped and riveted silver-plated beryllium copper cage	Synthetic graphite	0.00002 to 0.00015	Air mist	0.053 to 0.23	1026	910	996	0.17	0.09 to 0.25	18.7	No failure; cage not broken. Bearing was clean and free with slight film of graphite on bearing.
10	Stamped and riveted silver-plated beryllium copper cage	Dried synthetic graphite	0.00002 to 0.00015	Air mist (dry air)	0.053 to 0.23	1037	931	1010	0.09	0.07 to 0.28	18.5	No failure; cage not broken. Bearing friction torque only 0.09 in.-lb at 1000° F. Bearing was clean and free with slight film of graphite on bearing.
11	Two-piece riveted, machined cast Inconel cage. Oxide-coated.	MoS₂	0.00002 to 0.00015	Air mist	0.053 to 0.23	1054	953	1006	1.4	0.64 to 2.5	20.9	No failure; bearing not broken. Bearing friction torque was as high as 2.5 in.-lb at 1000° F. Yellow-white deposit at cage-locating surface.
12	Two-piece riveted, machined cast Inconel cage. Oxide-coated.	Synthetic graphite	0.00002 to 0.00015	Air mist	0.053 to 0.23	1018	928	994	0.33	0.20 to 0.36	19.6	No failure; cage not broken. Bearing friction torque was slightly erratic at all temperature levels. Bearing in good shape and free with slight film of graphite on bearing.
13	Two-piece riveted, machined cast Inconel cage. No oxide coating	Synthetic graphite	0.00002 to 0.00015	Air mist	0.053 to 0.23	----	940	1006	0.13	0.06 to 0.36	18.1	No failure; cage not broken. Bearing friction torque somewhat erratic but low. Bearing in good shape and free and slightly discolored.
14	Two-piece riveted, machined cast Inconel cage. Oxide-coated.	Silicone-diester blend[e]	0.0003 (15 drops/min)	Fluid drop	0	600	534	553	0.10	0.06 to 0.13	41.25	No failure; cage not broken. Bearing friction torque was steady and low for 29¼ hr at 550° F. It reached 1.5 in.-lb in 2 hr at 700° F. Heavy rubbery film deposit on bearing.

[a] Approximately 4 percent methacrylate polymer.
[b] 5 Percent tricresyl phosphate.
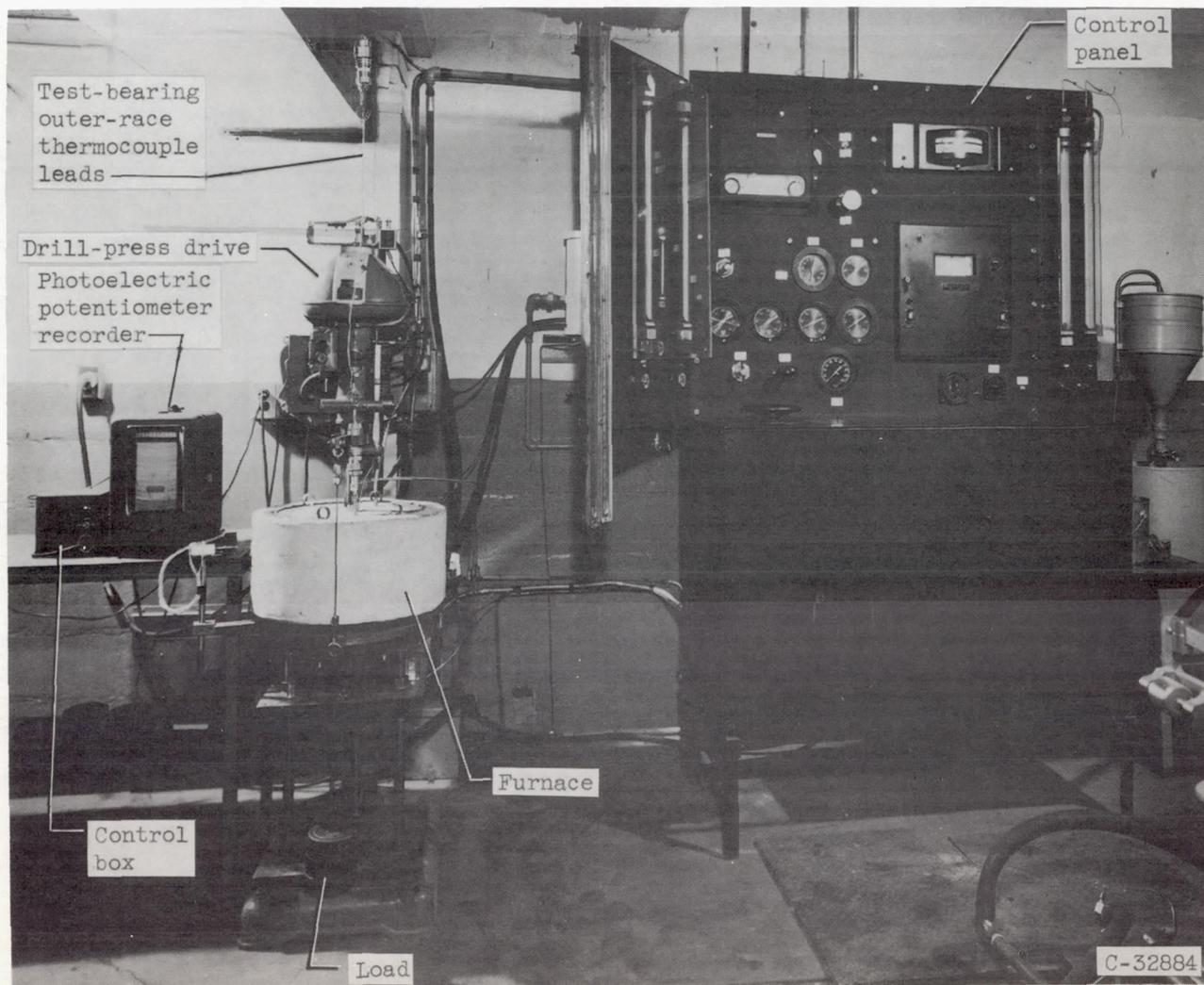[c] 0.5 Percent phenothiazine.
[d] 1 Percent phenyl-α-napthylamine.
[e] Silicone-diester blend:
    $\frac{1}{3}$ Di(2-ethylhexyl)sebacate + $\frac{2}{3}$ methylphenyl polysiloxane (100 centistokes at 77° F) Δ 0.5 percent phenothiazine. (Parts by volume.)
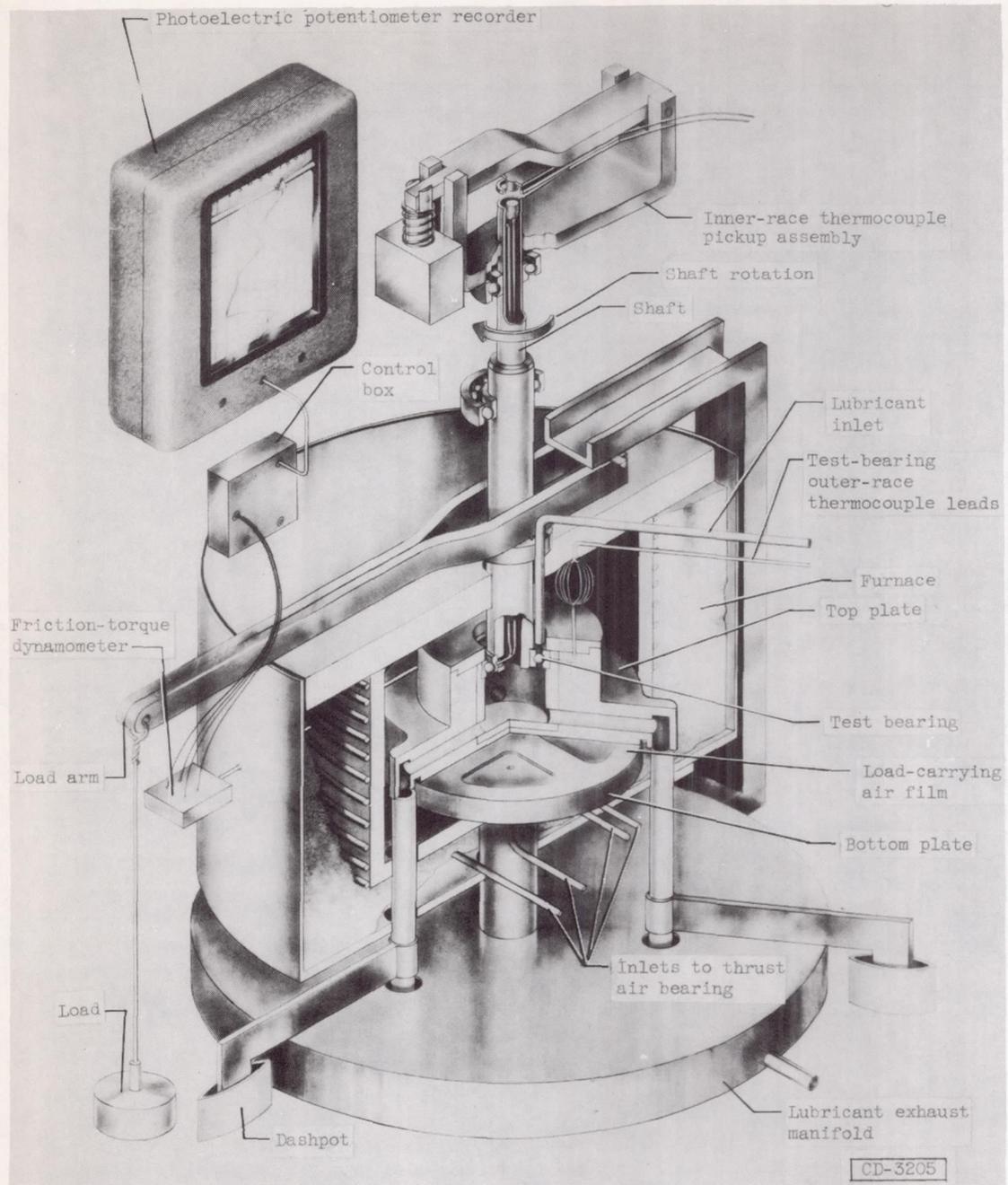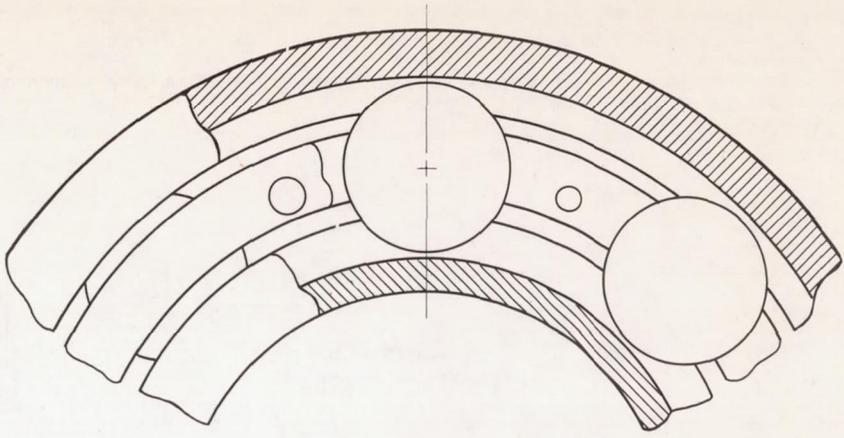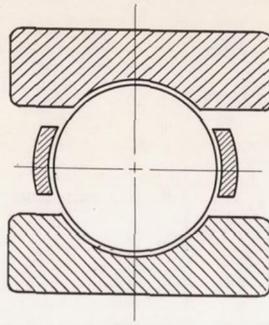
(a) Sketch showing details.
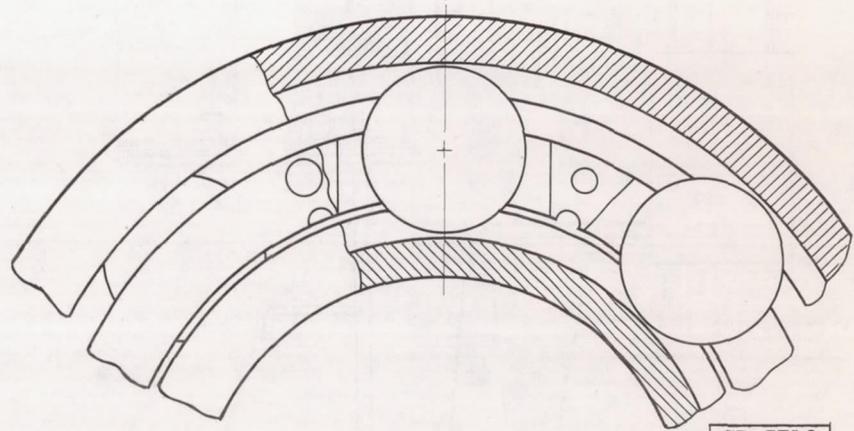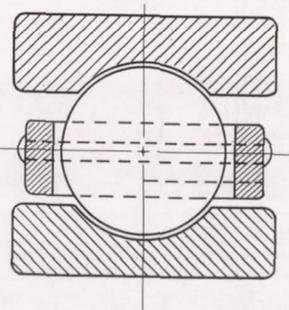
Figure 1. - High-temperature rig.

(b) Over-all view.

Figure 1. - Concluded. High-temperature rig.

(a) Two-piece, stamped and riveted silver-plated beryllium copper cage.

(b) Two-piece, riveted and machined cast Inconel cage.

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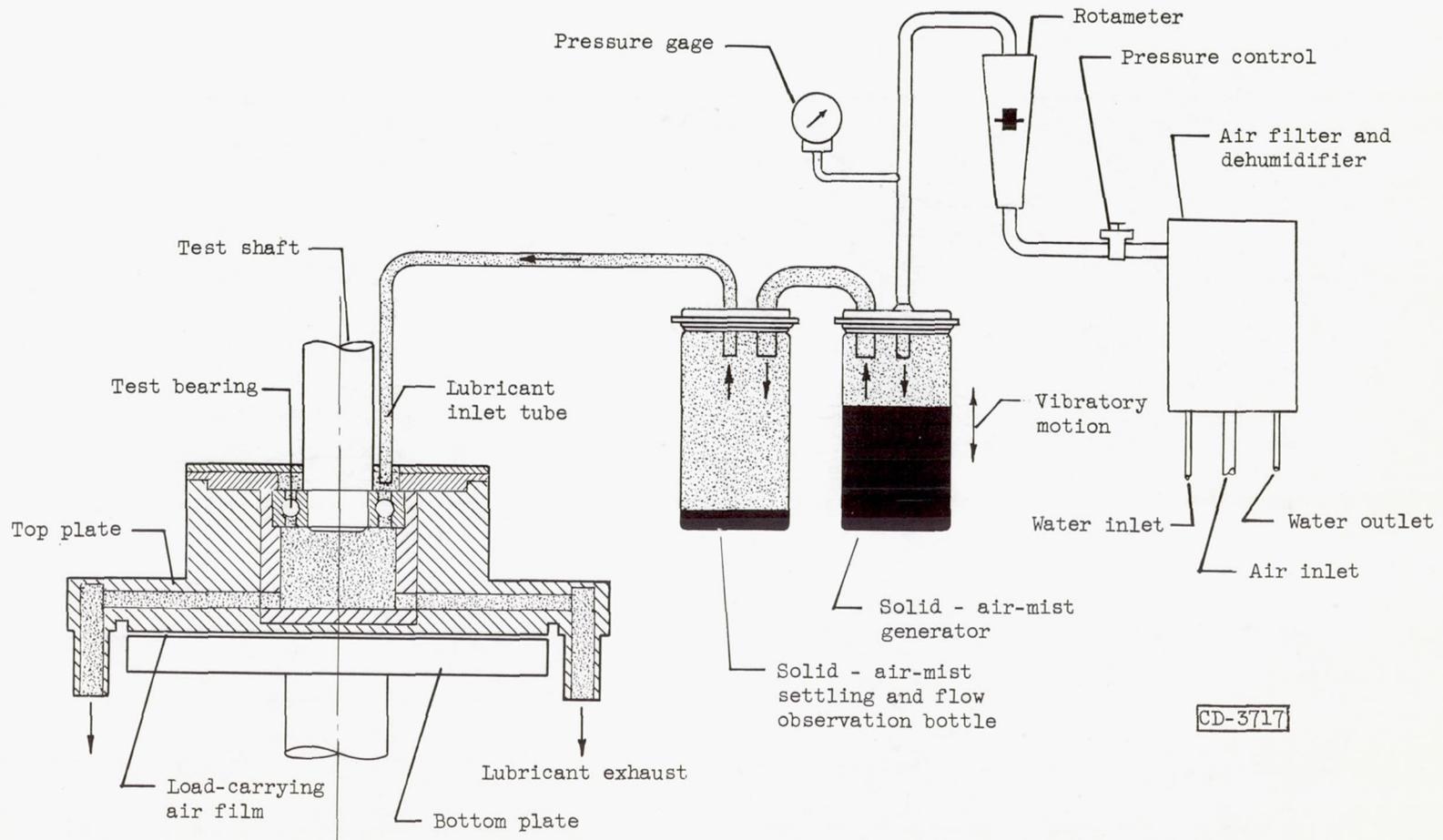Figure 2. - Schematic drawings of test bearings.

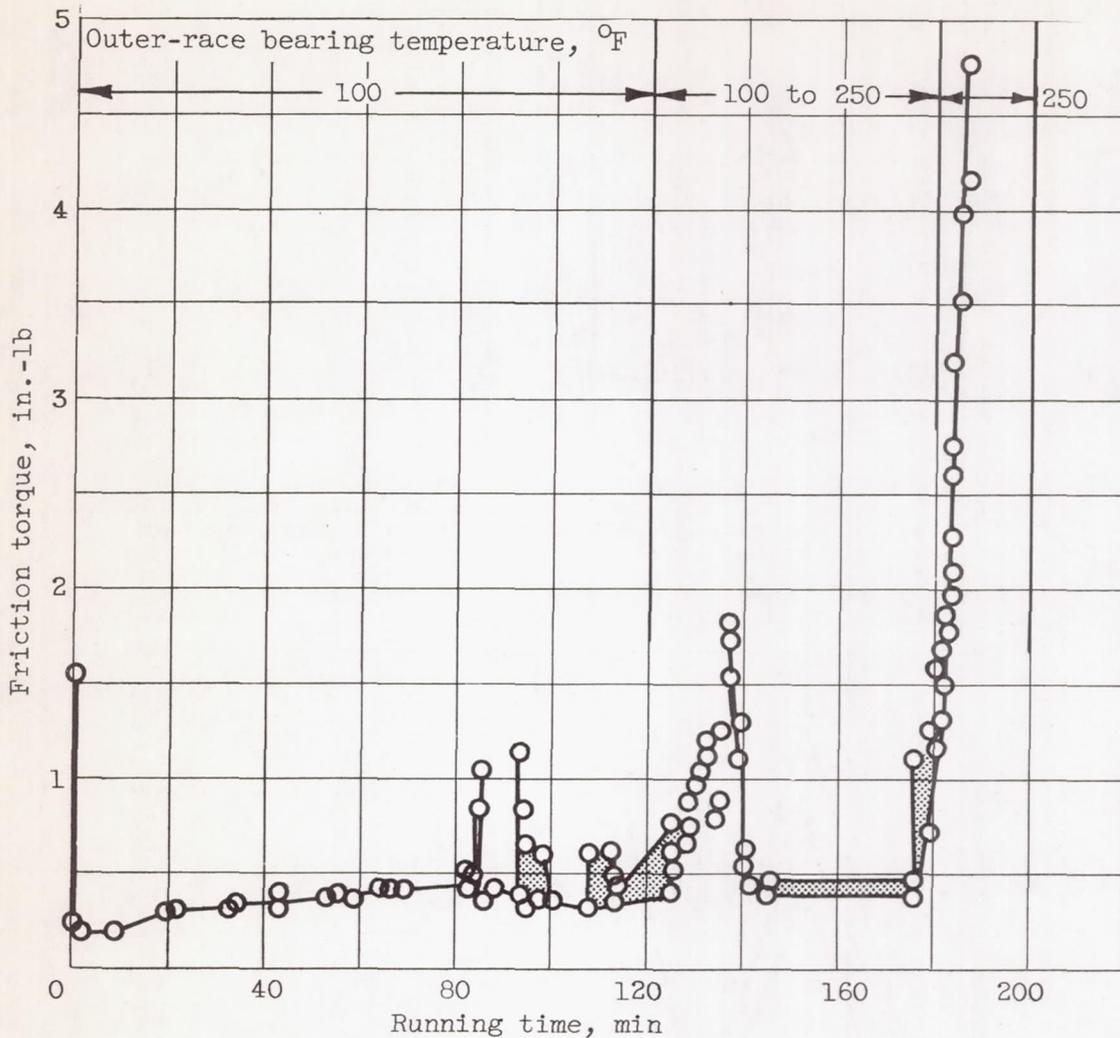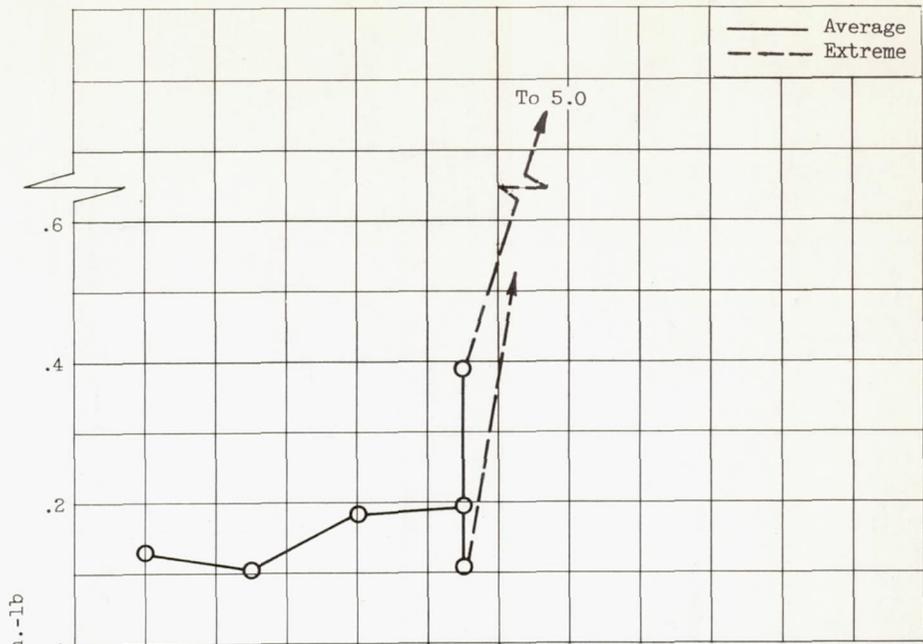Figure 3. - Solid-particle - air-mist lubrication arrangement.

Figure 4. – Test 1. Effect of running time on bearing friction
torque for dry operation. Speed, 2500 rpm; thrust load, 110
pounds; bearing construction, stamped and riveted silver-
plated beryllium copper cage.

(a) Test 2.   Lubricant, MIL-L-O-6081A grade 1010 oil; method, drop feed;
    lubricant flow rate, 0.0003 to 0.001 pound per minute (15 to 55 drops
    min).
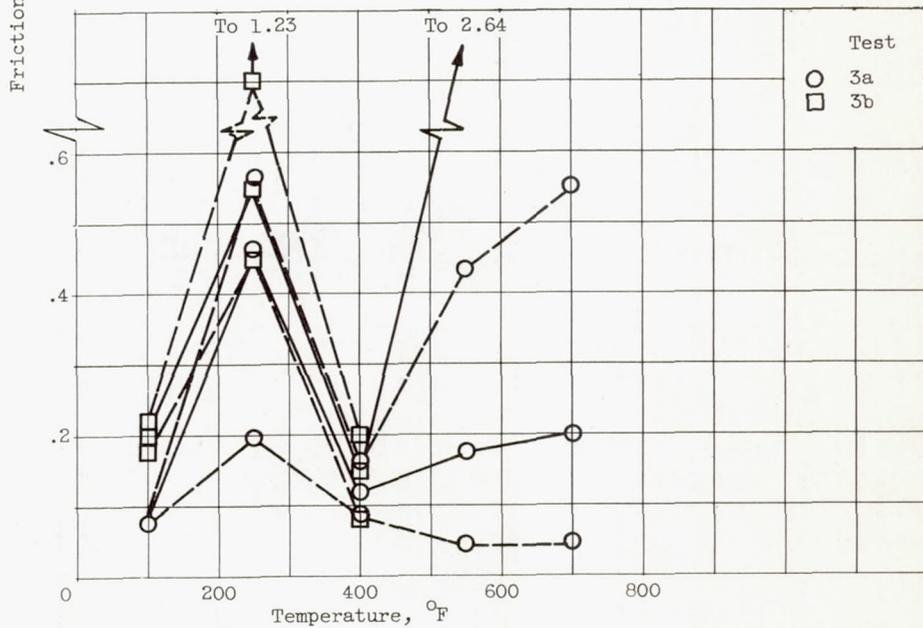
(b) Tests 3a and 3b.   Lubricant, MIL-F-5624B grade JP-4 fuel; method, drop
    feed; lubricant flow rate, 0.0002 to 0.0003 pound per minute (20 to 24
    drops/min).

Figure 5. - Effect of temperature on friction torque of bearings with
    silver-plated beryllium copper cages. Speed, 2500 rpm; thrust load,
    110 pounds.

(c) Tests 4a and 4b. Lubricant, di(2-ethylhexyl)sebacate + additives; method, drop feed; lubricant flow rate, 0.0003 to 0.001 pound per minute (15 to 55 drops/min).

(d) Test 5. Lubricant, dioctyl isooctene phosphonate + additives; method, drop feed; lubricant flow rate, 0.0003 pound per minute (15 drops/min).

(e) Test 6. Lubricant, tetrakis (2-ethylhexyl)silicate + oxidation inhibitor; method, drop feed; lubricant flow rate, 0.0003 pound per minute (15 drops/min).

(f) Test 7. Lubricant, silicone-diester blend; method, drop feed; lubricant flow rate, 0.0003 pound per minute (15 drops/min).

Figure 5. - Continued. Effect of temperature on friction torque of bearings with silver-plated beryllium copper cages. Speed, 2500 rpm; thrust load, 110 pounds.

(g) Test 8. Lubricant, MoS$_2$; method, air mist (air-flow rate, 0.053 to 0.23 cu ft/min); lubricant flow rate, 0.00002 to 0.00015 pound per minute.

Figure 5. - Continued. Effect of temperature on friction torque of bearings with silver-plated beryllium copper cages. Speed, 2500 rpm; thrust load, 110 pounds.
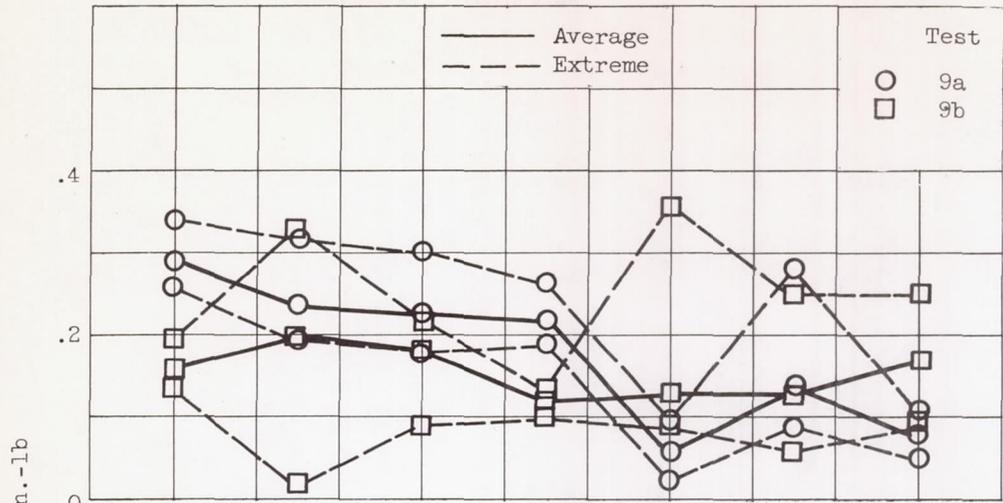
(h) Tests 9a and 9b. Lubricant, graphite; method, air mist (air-
    flow rate, 0.053 to 0.23 cu ft/min); lubricant flow rate, 0.00002
    to 0.00015 pound per minute.
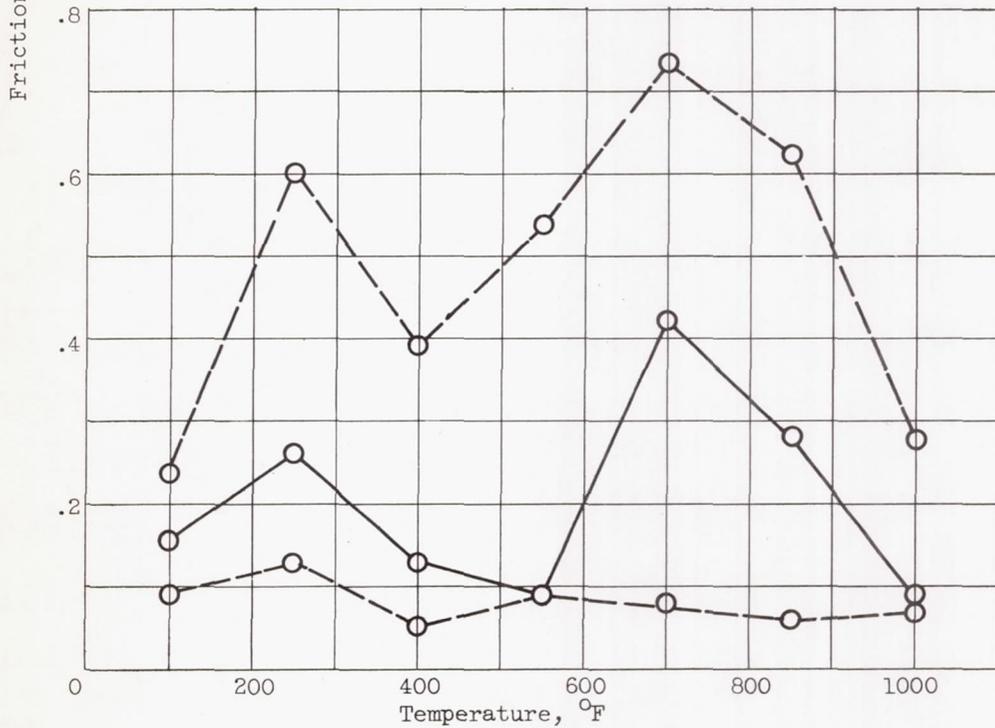
(i) Test 10. Lubricant, dried graphite (dry air); method, air mist
    (air-flow rate, 0.053 to 0.23 cu ft/min); lubricant flow rate,
    0.00002 to 0.00015 pound per minute.

Figure 5. - Concluded. Effect of temperature on friction torque of
    bearings with silver-plated beryllium copper cages. Speed, 2500
    rpm; thrust load, 110 pounds.
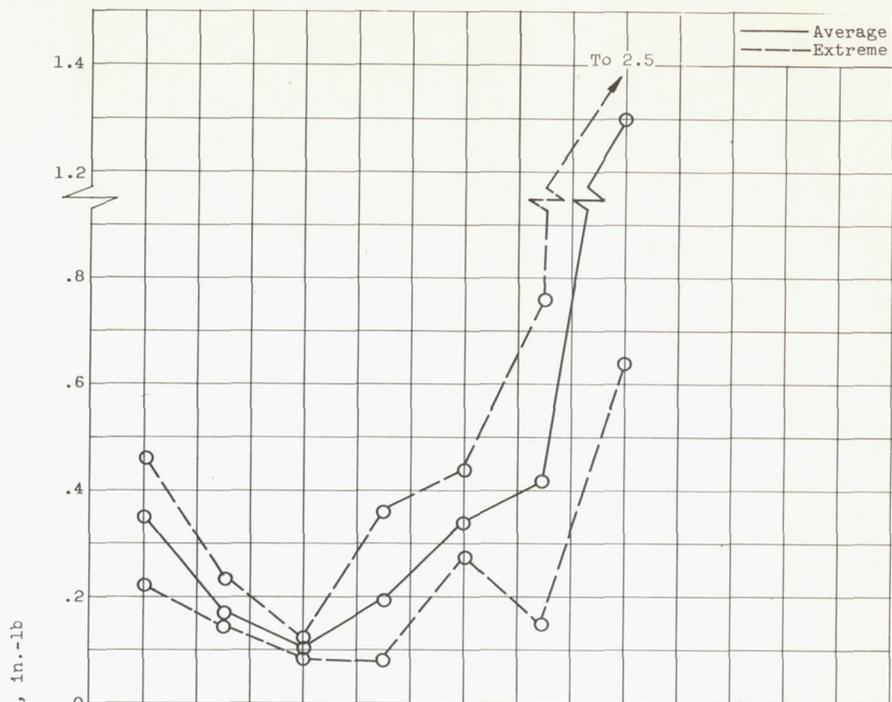
(a) Test 11. Lubricant, MoS$_2$; method, air mist (air-flow rate, 0.053 to
0.23 cu ft/min); lubricant flow rate, 0.00002 to 0.00015 pound per minute.
(Oxide-coated cage.)
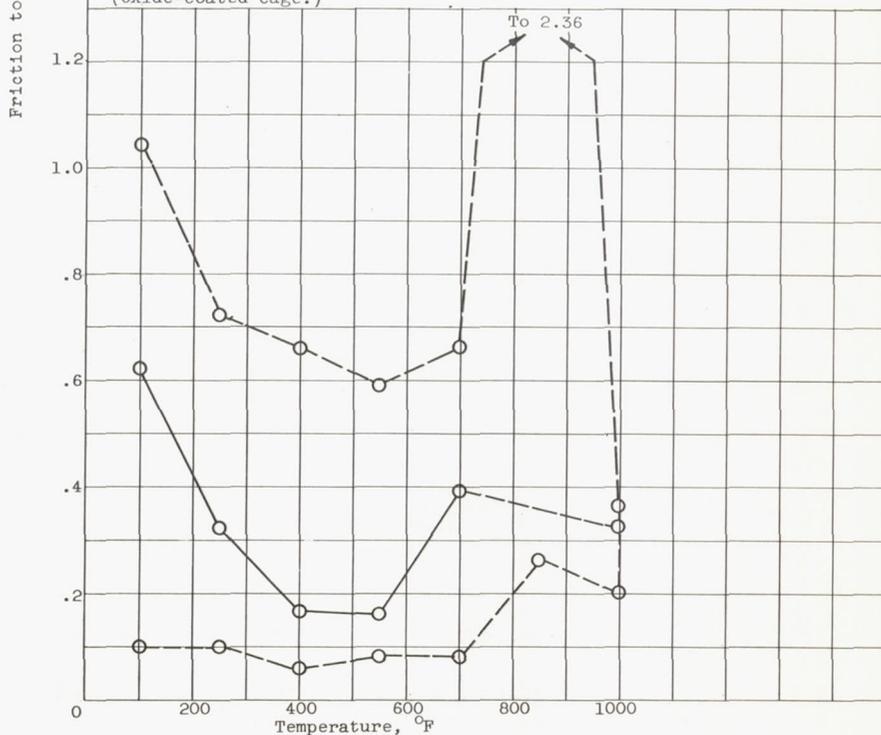
(b) Test 12. Lubricant, graphite; method, air mist (air-flow rate, 0.053 to
0.23 cu ft/min); lubricant flow rate, 0.00002 to 0.00015 pound per minute.
(Oxide-coated cage.)

Figure 6. - Effect of temperature on friction torque of bearings with Inconel
cages. Speed, 2500 rpm; thrust load, 110 pounds.
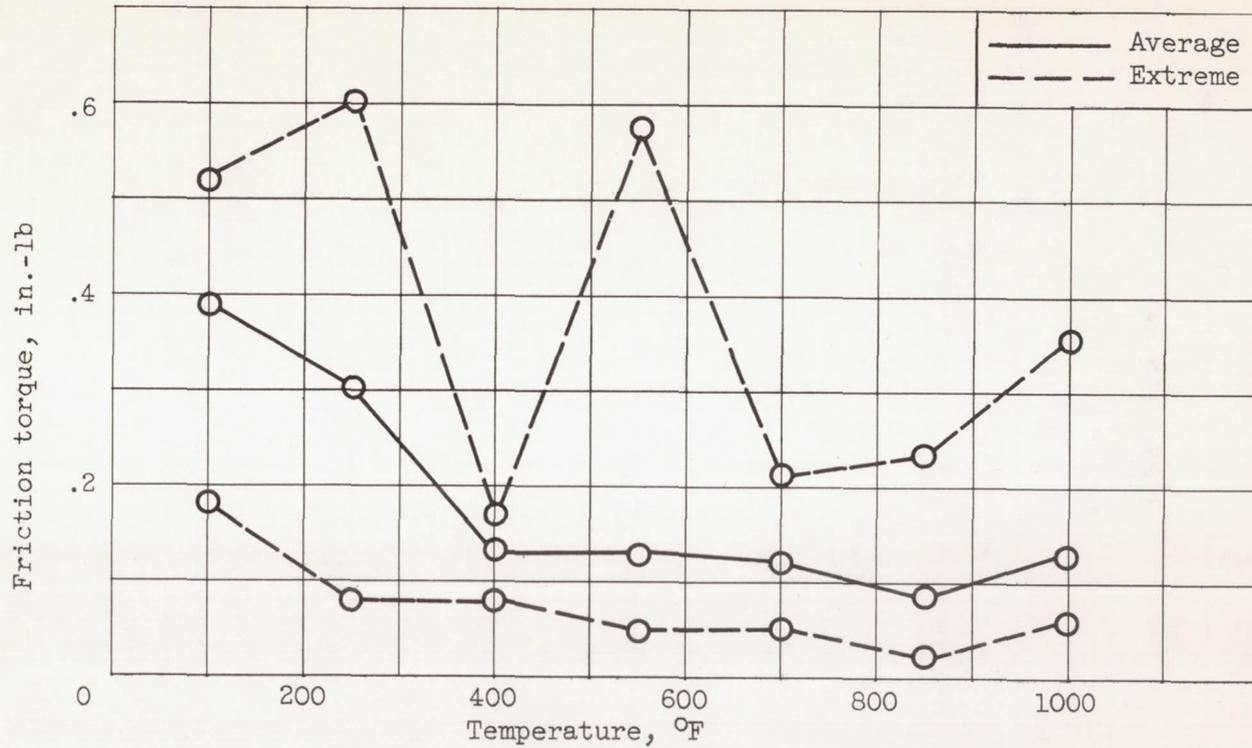
(c) Test 13. Lubricant, graphite; method, air mist (air-flow rate, 0.053 to 0.23 cu ft/min); lubricant flow rate, 0.00002 to 0.00015 pound per minute. (No oxide coating on cage.)

Figure 6. - Concluded. Effect of temperature on friction torque of bearings with Inconel cages. Speed, 2500 rpm; thrust load, 110 pounds.
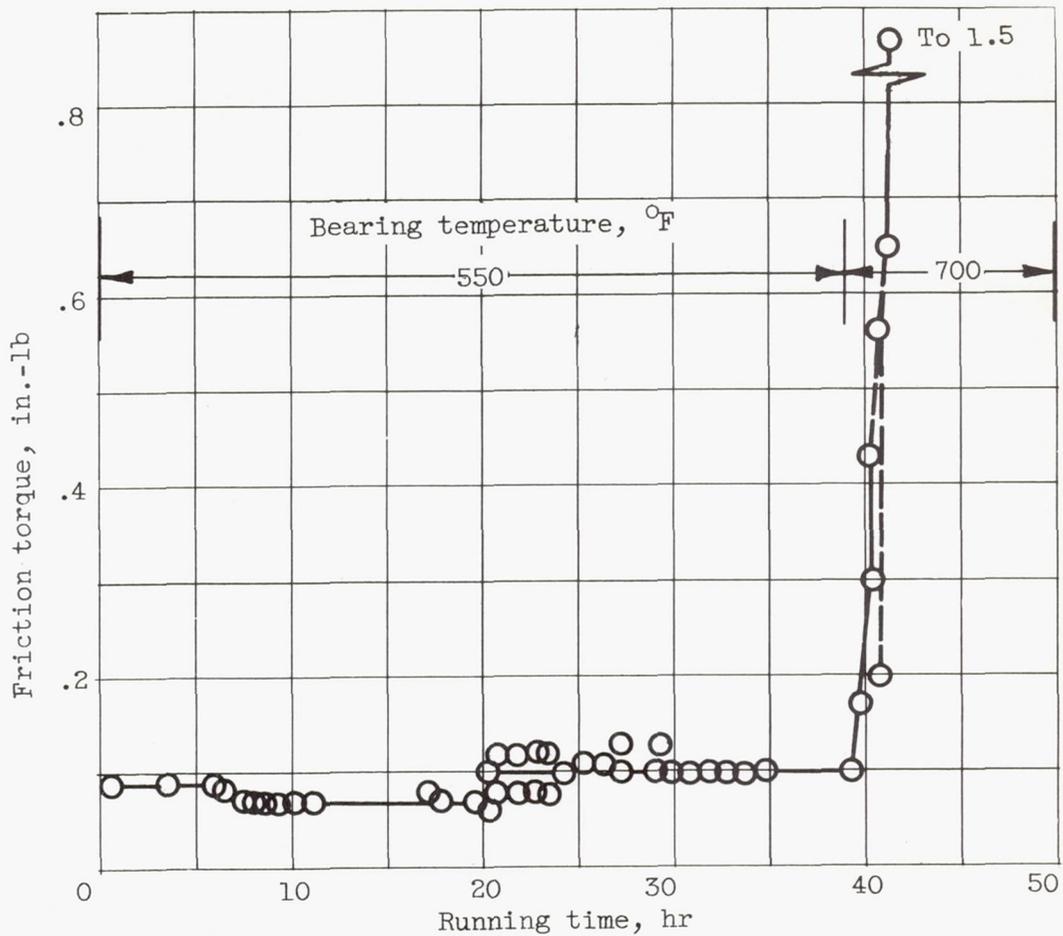
Figure 7. - Test 14. Effect of running time on friction torque
of bearing with oxide-coated cast Inconel cage. Speed, 2500 rpm;
thrust load, 110 pounds; lubrication method, drop feed; lubri-
cant flow rate, 0.0003 pound per minute (15 drops/min).
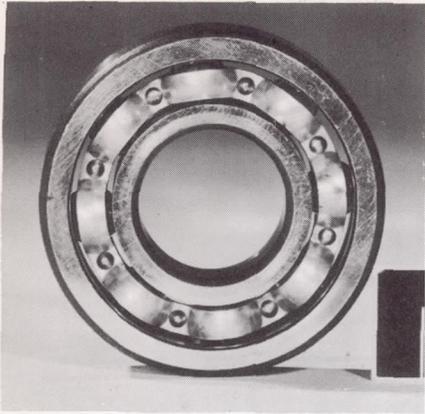
(a) New bearing, stamped and riveted silver—plated beryllium copper cage.
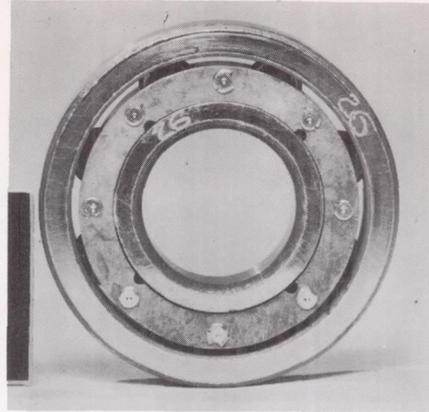
(b) New bearing, two-piece riveted and machined cast Inconel cage.
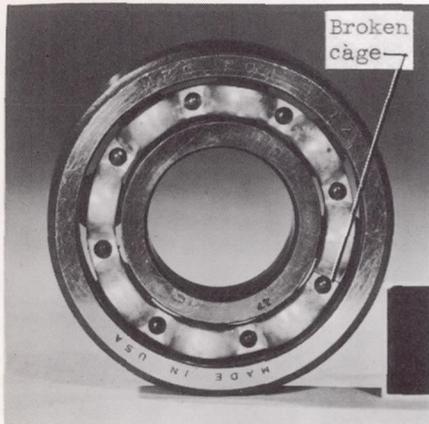
(c) Test 1; dry.
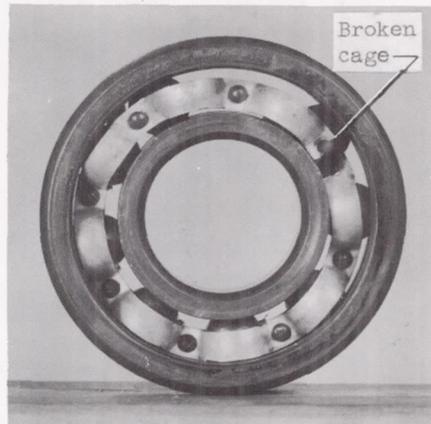
(d) Test 2; lubricant, MIL-O-6081A grade 1010 petroleum.
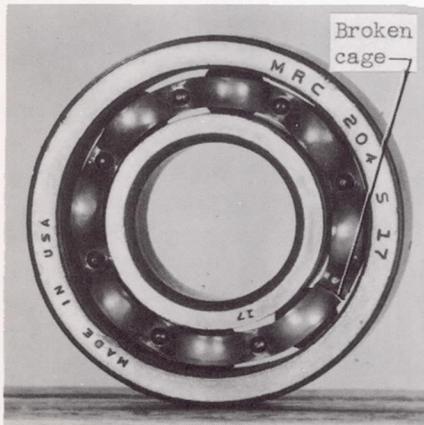
(e) Test 3a; lubricant, MIL-F-5624B grade JP-4 jet-engine fuel.
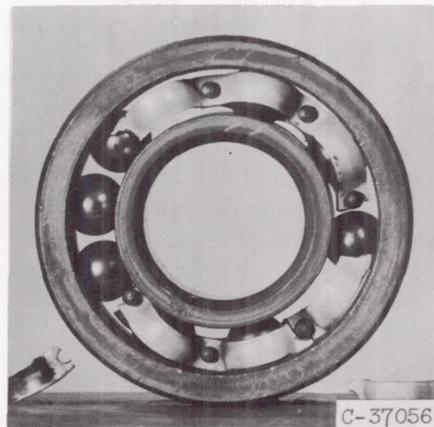
(f) Test 4a; lubricant, di(2-ethylhexyl)sebacate + additives.

Figure 8. - Test bearings before and after tests.

(g) Test 5; lubricant, dioctyl
    isooctene phosphonate.
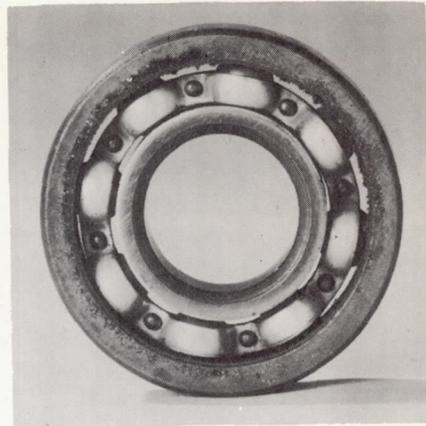
(h) Test 6; lubricant, tetrakis
    (2-ethylhexyl)silicate +
    oxidation inhibitor.
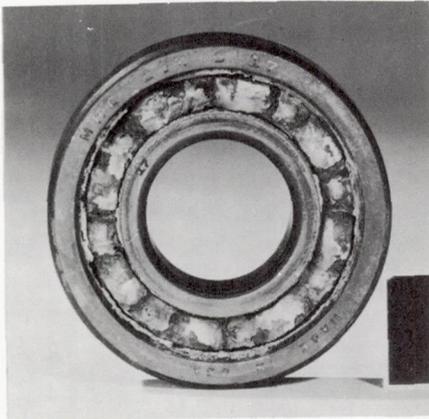
(i) Test 7; lubricant inlet side,
    silicone-diester blend.
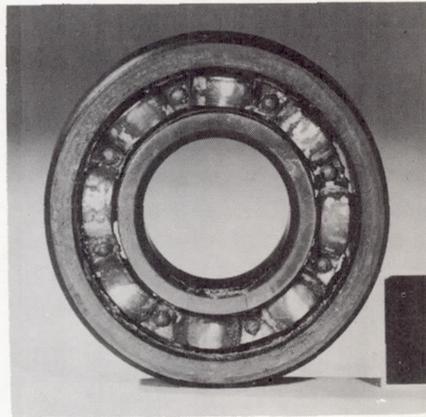
(j) Test 7; lubricant outlet side,
    silicone-diester blend.
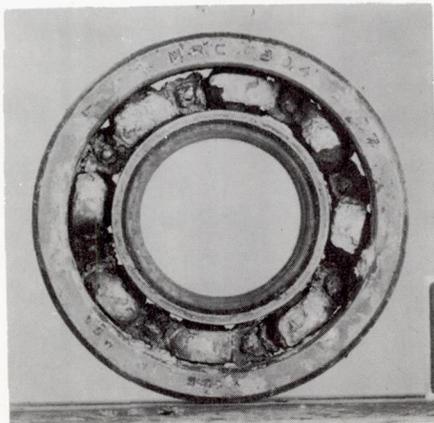
(k) Test 8; lubricant inlet side,
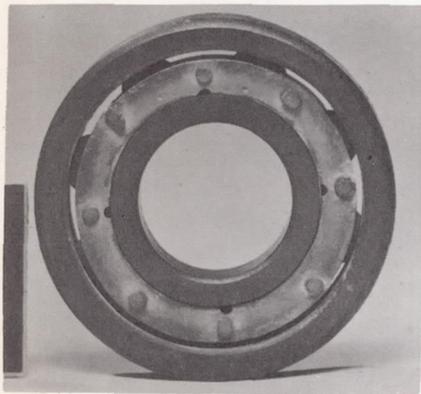 MoS_2.
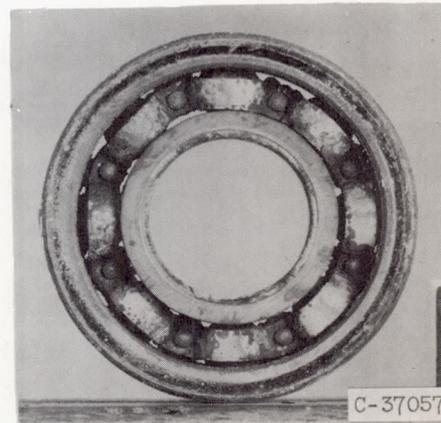
(l) Test 8; lubricant outlet side,
    MoS_2.

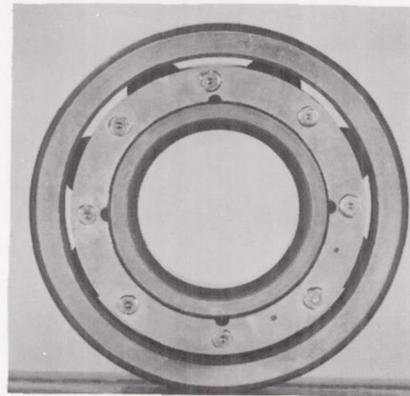Figure 8. - Continued. Test bearings before and after tests.
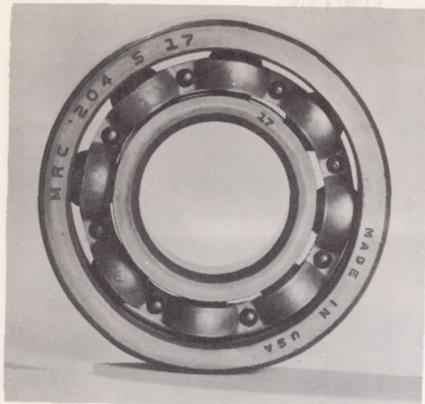
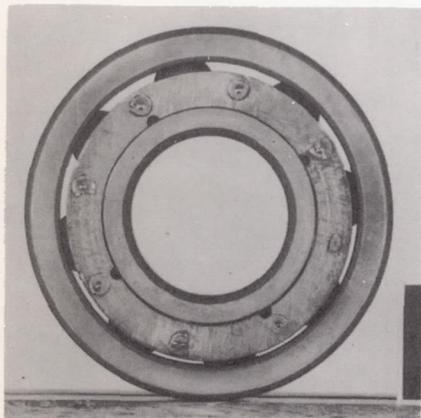(m) Test 9a; lubricant, graphite.
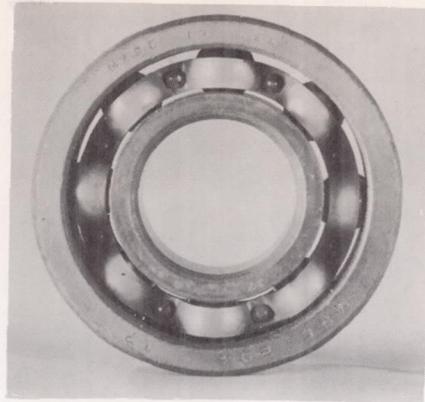
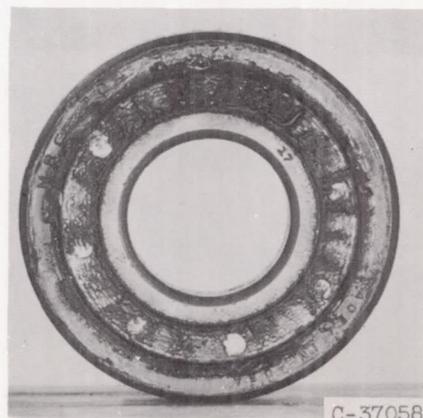(n) Test 10; lubricant, dried graphite (dry air).

(o) Test 11; lubricant, MoS_2; oxide-coated cast Inconel cage.

(p) Test 12; lubricant, graphite - air mist; oxide-coated cast Inconel cage.

(q) Test 13; lubricant, graphite; cast Inconel cage (no oxide coating).

(r) Test 14; lubricant, silicone - diester blend; oxide-coated cast Inconel cage.

Figure 8. - Concluded.   Test bearings before and after tests.