NACA

RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF MOLYBDENUM DISULFIDE - AIR-MIST LUBRICATION FOR ROLLER BEARINGS OPERATING TO DN VALUES OF 1×10^6 AND BALL BEARINGS OPERATING TO TEMPERATURES OF 1000° F

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY INVESTIGATION OF MOLYBDENUM DISULFIDE - AIR-MIST LUBRICATION FOR ROLLER BEARINGS OPERATING TO DN VALUES OF 1×10^6 AND BALL BEARINGS OPERATING TO TEMPERATURES OF 1000° F

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SUMMARY

A preliminary investigation of the effectiveness of molybdenum disulfide MoS_2 as a bearing lubricant at high temperature, and at high speeds was conducted. Molybdenum disulfide was applied in three ways: (1) by preparing the bearing before running with a MoS_2 syrup-bonded coating, (2) by lubricating the bearing during operation with a MoS_2-air mist spray, and (3) by a combination of the MoS_2 syrup-bonded precoating and the MoS_2-air mist methods.

The high-temperature evaluation was conducted with 1-inch-bore ball bearings equipped with two piece, stamped and riveted steel cages over a range of ambient temperatures from room temperature to 1000° F; and DN values (product of bearing bore in mm and shaft speed in rpm) from 0.04×10^6 to 0.09×10^6 at a thrust load of 20 pounds. The test bearings were lubricated with MoS_2-air mist at the rate of 0.35 to 0.7 ounce per hour.

The high-speed evaluation was conducted in a radial-load rig with three types of 75-millimeter-bore (size 215) cylindrical-roller bearing: (a) cageless roller bearings, (b) one-piece inner-race-riding cage-type bearings, and (c) two-piece roller-riding cage-type bearings. Bearing DN values were varied from 0.3×10^6 to 0.975×10^6, the radial load was 368 pounds, and all three methods of lubrication were used.

A 1-inch-bore ball bearing operated satisfactorily for 6 hours when lubricated only by a MoS_2-air mist at a speed of 1725 rpm a thrust load of 20 pounds, and at an ambient temperature that was progressively increased in 200° increments from 400° to 800° F. The bearing failed, however, when the temperature was subsequently increased to 1000° F. In a duplicate test, a second bearing ran

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successfully for 1 hour at 1000° F for a total running time of 8.4 hours at which time the test was terminated for inspection of the bearing. The bearing surface was found to be badly oxidized.

A size 215 cylindrical, cageless roller bearing provided with a MoS_2 syrup coating before operation and lubricated only with MoS_2–air mist during operation ran satisfactorily for 11.8 hours without showing signs of wear or surface damage. The run was conducted at a load of 368 pounds and at DN values which were increased progressively from 0.3×10^6 to 0.975×10^6 (13,000 rpm). The maximum bearing temperature was 386° F.

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Roller-riding and inner-race-riding bronze (brass) cage-type bearings when subjected to similar conditions indicated a lower limiting DN than the cageless-type bearings and showed signs of considerable wear.

Lubrication provided solely by a syrup-bonded coating of MoS_2 over all bearing surfaces was not effective in lubricating size 215 cylindrical-roller bearings subjected to a load of 368 pounds.

Operation of bearings without lubrication resulted in failures of both inner-race-riding and cageless roller bearings after relatively short periods of operation.

INTRODUCTION

A lubricant or a means of lubrication has been sought that will allow operation of parts in rolling and sliding contact beyond a temperature range of -65° to 400° F and at extreme speeds in certain applications. Oil-air mist and circulating oil-jet methods of lubrication are at present employed and are limited in use to the aforementioned temperature range. Synthetic lubricants offer promise of improvement over mineral oils and greases, although they are at present limited to temperatures below 500° F (references 1 and 2).

Friction between surfaces in sliding contact is effectively reduced when a syrup-bonded coating of molybdenum disulfide MoS_2 is present between the surfaces (reference 3). Although a preliminary investigation of roller bearings coated with syrup-bonded MoS_2 and run dry (results reported herein) showed excessive wear after limited operation at low speeds, the results were sufficiently promising to indicate the possibilities of MoS_2 as a bearing lubricant. An investigation was therefore conducted at the NACA Lewis laboratory to determine the relative merits of a new and unique lubrication technique hereinafter referred to as "molybdenum disulfide - air mist" lubrication. The results of this investigation for MoS_2-air mist, in particular, are reported herein for:

(a) High temperatures and low speeds

(b) High speeds and normal temperatures

The investigation was not conducted at the combined conditions of high speeds and high temperature because of the preliminary nature of the work. It is emphasized that this investigation is of preliminary nature, and that all tests were conducted with commercially available bearings. The results are considered to be worth reporting at this time, however, in that the high temperature and the high-temperature high-speed lubricant problem is at present very critical in certain applications such as guided missiles and rockets.

The high-temperature evaluation was conducted with 1-inch-bore ball bearings equipped with two-piece, stamped and riveted steel cages. For comparison, these bearings, a few of which were surface treated to form a film of ferroso ferric oxide Fe_3O_4, were operated both dry and with MoS_2-air mist lubrication. The operating variables were as follows: ambient temperatures approximately 400°, 600°, 800°, and 1000° ±40° F; speeds, 1725 and 3400 rpm; load, 20 pounds thrust; MoS_2 flow rate, 0.35 to 0.7 ounce per hour; and lubricant air pressure 0.3 to 0.8 inch of mercury.

The high-speed evaluation was conducted with three types of conventional 75-millimeter-bore cylindrical-roller bearing. One type was equipped with 18 cylindrical rollers, 0.5513-inch diameter by 0.551 inch long, spaced by a one-piece inner-race-riding bronze (brass) cage; a second type was equipped with 17 cylindrical rollers, 0.5255-inch diameter by 0.650 inch long, spaced by a two-piece roller-riding bronze (brass) cage; and the third type was a cageless roller bearing equipped with 21 cylindrical rollers, 0.5635-inch diameter by 0.5625-inch long.

For comparison, these bearings were operated dry, and with the following lubricating techniques: circulating oil through a single jet, MoS_2- syrup coating, MoS_2- syrup coating over liquid honed surfaces, and MoS_2-air mist (two methods). The operating variables were as follows: DN, 0.3×10^6 to 0.975×10^6 (4000 to 13,000 rpm); load, 368 pounds radial; MoS_2 flow rate, 0 to 1.6 ounces per hour; air pressure, 0 to 12 inches of mercury, and oil flow, 2.75 pounds per minute.

APPARATUS

High-temperature rig. - The high-temperature rig (fig. 1), consisted of a modified drill press, a small cavity resistance furnace, a spindle, and a test bearing housing.

The test bearing was mounted on a spindle driven by the drill press. Modifications made to the drill-press facilitated axial loading of the test bearing. The outer race of the test bearing was seated in a fixture located at the bottom of the furnace cavity. The fixture was so designed that the test bearing would not be loaded in the radial direction by differential thermal expansion between the furnace, the fixture, and the outer race of the test bearing (fig. 1(a)). 2257

The drill press was modified in that the rack and pinion were replaced by a load arm (fig. 1(b)) which loaded the spindle vertically downward without introducing a horizontal component of the load on the spindle supports. This alteration made it possible to obtain reproducible calibrations of the thrust load applied to the test bearing. The spindle was driven by a 1/3 horsepower, 1725 rpm motor. The spindle speeds available were 460, 900, 1725, 3400, and 6300 rpm.

The furnace (fig. 1(a)) consisted of an 8-inch diameter by $5\frac{1}{4}$ inch high cylinder of Inconel with a $2\frac{1}{8}$ inch by $3\frac{1}{4}$ inch cavity in the center. The Inconel block was heated by the power loss in a coil of chromel wire of 6 ohms resistance wound around the block. The cavity temperature was regulated by means of a continuously adjustable autotransformer, which controlled the voltage output of the 110-volt source. The furnace was equipped with an automatic temperature control.

The outer-race bearing temperature, as well as the wall temperature of the cavity at its bottom center, was obtained by means of chromel-alumel thermocouples and a potentiometer with a cold junction.

The lubricating system was designed to supply MoS_2-air mist to the vicinity of the bearing. The system consisted of a low-pressure air supply, a pressure-regulating valve, an air filter, a 6.5-ounce bottle of MoS_2 (the average particle size in percent by weight is given in table I), and a length of 1/16-inch copper tubing from the MoS_2 bottle to the vicinity of the test bearing. The MoS_2 bottle was slightly pressurized to agitate the lubricant. Air leaving the bottle through the 1/16-inch tube carried particles of MoS_2 with it to the bearing. The MoS_2-air lubricant mist was directed to a point just beneath the test bearing in the furnace cavity (fig. 1(a)). A large portion of the solid particles of MoS_2 fell to the cavity bottom without contacting the bearing. Air pressure carried the finer particles to the test bearing for lubrication.

Test bearings used in high-temperature investigation. - The physical characteristics of the test bearings used in the high-temperature rig are given in table II. These bearings were standard ball bearings with two-piece, stamped and riveted steel cages (fig. 2). The bearings 2257 were of the inch series, the dimensions being: bore, 1 inch; outside diameter, 2 inches; and width, 3/8 inch. The inner race, outer race and balls were of SAE 52100 steel.

A caustic potassium nitrate treatment was used to form a black tenacious film of ferroso ferric oxide Fe_3O_4 on the surfaces of two of the bearings. The clean bearings were immersed successively in two baths, each of which consisted of one part potassium nitrate KNO_3 and two parts sodium hydroxide NaOH. The baths were kept at 141° and 154° C by dilution with water. The immersion time in each bath was not critical. After immersion the bearings were washed in boiling water and dried in clean air.

High-speed rig. - The high-speed bearing rig (fig. 3) used for this investigation is described in references 4 and 5. The bearing under investigation was mounted on one end of the test shaft, which was supported in cantilever fashion, for observation of bearing component parts and lubricant flow during operation. Radial load was applied to the experimental bearing by means of a lever and dead weight system in such a manner that the outer race of the experimental bearing was essentially unaffected by small shaft deflections or by small shaft and load arm misalinements. The drive equipment is described in reference 4. The speed range of the test shaft was 800 to 50,000 rpm.

The method of temperature measurement is described in reference 4. Briefly, for the test bearing, outer-race bearing temperatures were measured by means of six iron-constantan thermocouples located at 60° intervals around the outer-race periphery at the axial center line of the bearing under investigation. Inner-race bearing temperatures were measured by means of a copper-constantan thermocouple pressed against the inner-race inside surface at the axial midpoint of the bearing, the voltage being transmitted from the rotating shaft by means of slip rings.

The support bearings were lubricated in the manner described in reference 4. A double felt seal was installed on the shaft between the center support bearing and the test bearing for all dry runs, MoS_2 syrup-bonded film runs, and MoS_2-air mist runs. A suction fan was installed between the support bearings to cause a slight flow of air from the test section through the shaft seal. These precautions were taken to prevent oil and oil mist from entering the test bearing section of the rig. (The felt seal heated the test shaft somewhat, the exact amount depending on the shaft speed and previous seal operating time. Therefore, precise comparisons between runs with and without the seal should not be attempted.)

Molybdenum disulfide syrup-bonded coatings (references 3 and 6) were applied to bearings 12, 13, 14, and 15 (table III). A new technique was used with bearings 12 and 13. All the surfaces of these two bearings were first liquid honed with number 80 grit before the coating of MoS_2 syrup was applied. This sequence of treatments provided a somewhat more tenacious film of MoS_2 on both the steel and brass surfaces of the test bearings. 2257

Two MoS_2-air mist systems were employed (fig. 4). The single-opposed jet system is illustrated in figures 4(a) and 4(b) and the modified-single-jet system is shown in figure 4(c). The operation of bearings 15 (cageless) and 16 (one-piece inner-race-riding cage type) were particularly sensitive to the amount of MoS_2 supplied by the air stream of the single-opposed MoS_2-air mist jet system. This system proved faulty because it did not deliver a constant amount of MoS_2 per unit time when the supply air pressure was maintained constant. The faulty operation was due presumably to the intermittent clogging and breaking away of agglomerations of MoS_2 particles in the feed lines. Accordingly, a modified-single-jet system was designed (fig. 4(c)) to disperse the solid MoS_2 particles in such a manner that the larger particles would fall away from the bearing. In order to accomplish this distribution, a second air jet was introduced perpendicular to the MoS_2-air jet. The pressure of this air jet was adjusted so that only the smaller particles were carried to the bearing.

Test bearings used for high-speed investigation. - The physical characteristics of the seven test bearings used in the high-speed rig are given in table III. Three types of cylindrical-roller bearing were investigated (fig. 5). One type was a conventional roller bearing equipped with 18 cylindrical rollers, 0.5513-inch diameter by 0.551 inch long, spaced by a one-piece inner-race-riding brass cage; the second type was a conventional roller bearing equipped with 17 cylindrical rollers, 0.5255-inch diameter by 0.650 inch long, spaced by a two-piece roller-riding brass cage, and the third type was a cageless roller bearing equipped with 21 cylindrical rollers, 0.5635-inch diameter by 0.5625-inch long. All three types had the following dimensions: bore, 75 millimeters; outside diameter, 130 millimeters; and width, 25 millimeters. Two each of the first two types of bearing and three of the cageless type were investigated.

The test bearing measurements were obtained in the manner described in reference 4.

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PROCEDURE

High-temperature study. - The first runs were conducted at a constant speed of 1725 rpm and a thrust load of 20 pounds. The bearings were operated both dry and with MoS_2-air mist, in which case solid particles of MoS_2 were carried by the air stream to a point just beneath the test bearing. Most of the particles of MoS_2 did not work through the test bearing but settled out of the air stream and collected in the space in the bearing housing just below the test bearing. The flow of the lubricant was so adjusted that a fine mist issued from the bearing.

Inadequate lubrication was evidenced by a squeaky test bearing. If during the run, operation became squeaky, additional lubricant was supplied until more quiet operation was obtained. A grating sound indicated an excessive supply of lubricant to the test bearing.

The runs were conducted over a range of ambient temperatures. For comparison purposes, a few runs were conducted with no external heat supplied to the bearing. Two additional runs were made with an initial furnace-block ambient temperature of 800° F, a speed of 3400 rpm, and a thrust load of 20 pounds. During these runs the amount of heating power was kept constant. The third group of runs was conducted with an initial block ambient temperature of 400° F. The furnace-block temperature was increased in 200° F increments until failure of the test bearing occurred. The shaft speed was 1725 rpm and the thrust load 20 pounds. The bearing was operated continuously during the time required to reach the desired ambient temperature and for 1 hour after the designated ambient temperature had been reached. The test was terminated when failure of the test bearing occurred. Criterions of test bearing failure were slippage of the drive belt or rotation of the test bearing outer race or both.

High-speed study. - The effect of the various lubricants and lubrication methods on the operating temperatures of three types of roller bearing was determined over a range of DN values and at a constant radial load of 368 pounds. The one-piece inner-race-riding cage-type bearings were run (a) lubricated with oil, from an 0.089-inch-diameter jet at a lubricant flow of 2.75 pounds per minute, directed perpendicularly to the bearing face and aimed at the cage-locating surface (data from reference 4, bearing 6); (b) dry, uncoated; and (c) lubricated with MoS_2-air mist supplied through either single-opposed jets or the modified-single jet. The two-piece roller-riding cage-type bearings were run with (a) MoS_2-syrup coating over conventional bearing surfaces with no other lubrication, and (b) MoS_2-syrup coating over liquid-honed bearing surfaces with no other lubrication. The cageless full-complement roller bearings were run (a) lubricated with oil, from an 0.089-inch-diameter jet at a lubricant flow of 2.75 pounds per minute, directed perpendicularly to the bearing face and aimed at the inner-race-flange outside diameter, (b) with MoS_2-syrup coating over conventional bearing surfaces with MoS_2-air mist lubricating, (c) with MoS_2-syrup coating over liquid-honed bearing surfaces with no other lubrication, and (d) dry and uncoated.

The properties of the lubricating oil used are given in figure 6. This oil was a commercially prepared blend of a highly refined paraffin base with a small percentage of a polymer added to improve the viscosity index.

RESULTS AND DISCUSSION

High-Temperature Investigation

The high-temperature investigation consisted of six tests, which are summarized in table II. Three tests were run without any lubricant. In all cases, the bearings were thoroughly degreased by washing several times in a solvent and blowing with air. The dry runs were so conducted that a comparison might be made between the bearing operating characteristics with and without the MoS_2-air mist lubrication.

Test 1. - Test 1 was conducted with bearing 501, which had been Fe_3O_4 coated. The test was run at room temperature, a speed of 1725 rpm, and a thrust load of 20 pounds with no lubricant supplied to the test bearing. Failure occurred after 79 minutes because of cage breakage.

Test 2. - Test 2 was conducted with bearing 502. The bearing, which was uncoated, was run dry at room temperature, a speed of 1725 rpm, and a thrust load of 20 pounds. Failure occurred after 2 hours and 27 minutes. A small section of the cage had broken away and jammed between the races causing the outer race to rotate. The balls, cage, and parts of the race ways of the bearing were discolored from over-heating although the maximum measured temperature at the outer race did not exceed 187° F.

Test 3. - Test 3 was conducted with bearing 503, which had been Fe_3O_4 coated. The bearing was lubricated with a MoS_2-air mist and ran satisfactorily at a speed of 1725 rpm, and a thrust load of 20 pounds at ambient temperatures of 400°, 600°, and 800° F for a period of 1 hour at each temperature after the desired ambient temperature had been attained. Failure occurred during operation as the ambient temperature was being increased from 800° to 1000° F. The total running time was 6 hours. Failure was due to jamming of the bearing, which caused the outer race to rotate in its housing. Jamming of the bearing resulted, in the main part, from the building up of iron oxides on the bearing surfaces. The loss of bearing clearance apparently was not due to the packing of MoS_2 within the bearing.

Test 4. - Test 4 was conducted with bearing 504. This uncoated bearing was run at a speed of 1725 rpm and a thrust load of 20 pounds with MoS_2-air mist lubrication at ambient temperatures of approximately 400°, 600°, 800°, and 1000° F. A period of 1 hour at each temperature was maintained after the desired ambient temperature had been reached. Bearing failure did not occur although the diametral clearance within the bearing increased from 0.0003 to 0.0007 inch. The total running time was 8.4 hours.

Test 5. - Test 5 was conducted with bearing 505. This uncoated bearing was operated dry at a speed of 3400 rpm and a thrust load of 20 pounds. The ambient furnace-block temperature was set at 800° F at the start of the test. Bearing failure occurred after 6 minutes of operation, the steel cage having been fractured in several places.

Test 6. - Test 6 was conducted with bearing 506, an uncoated bearing run with MoS_2-air mist lubrication at a speed of 3400 rpm, a thrust load of 20 pounds, and an ambient furnace temperature of 800° F. Bearing failure occurred after 67 minutes of operation, apparently as a result of binding of the bearing due to oxides of iron. Although one-half of the steel cage had fractured slightly near a rivet, this fracture did not cause the bearing to jam.

Comparison of MoS_2-air mist and dry runs. - It is evident that the MoS_2-air mist shows promise of effective lubrication at temperatures as high as 1000° F.

Bearings made of alloy steels having nonoxidizing properties at elevated temperatures would apparently operate with less wear because, in all probability, the iron oxides act as an abrasive within the bearing and also promote the tendency of the bearing to bind. Stronger cages made of a material having good frictional properties at both low and high temperatures would greatly add to the bearing reliability at elevated temperatures.

Although no conclusive evidence can be drawn from the few tests reported herein, it is evident at least that the Fe_3O_4 coating did not result in any improvement of bearing performance. 2257

The short cage life at the higher speed (3400 rpm) may be attributed in part to the general unsuitability and weakness of a stamped and riveted steel retainer for this application.

High-Speed Investigation

The high-speed part of the investigation reported herein, tests 7 to 13, consisted in a comparison of dry operation, operation with MoS_2-air mist, MoS_2 syrup-bonded coating, MoS_2 syrup-bonded coating after liquid honing, and operation with oil lubrication. The results of the high-speed investigation are summarized in table III.

A brief description of each test is given and the individual high-speed-test results are followed with a general discussion of the relative merits of the various techniques of lubrication reported herein.

Test 7. - Test 7 was conducted with bearing 10 (one-piece inner-race-riding bronze (brass) cage). The bearing was run dry and uncoated at a radial load of 368 pounds. The bearing ran at DN values of 0.3×10^6 and 0.375×10^6 but failed after having operated for 9 minutes at a DN value of 0.45×10^6. The total running time was 2.15 hours. Failure was due to excessive cage wear in the roller pockets, which resulted in a brass build-up on the rollers, and in the eventual binding and fracturing of the cage in several places (fig. 7(a)).

The bearing running temperatures at the various speeds were not excessive. At DN values of 0.3×10^6, 0.375×10^6, and 0.45×10^6, the outer-race-maximum temperatures were 106°, 126°, and 195° F, respectively, and the inner-race temperatures were 104°, 132°, and 201° F, respectively. Temperatures at the DN value of 0.45×10^6 were obtained immediately after failure of the test bearing and are not equilibrium running temperatures. Upon disassembly, tempering colors indicated inner- and outer-raceway contacting-surface temperatures of 500° to 550° F (fig. 7(a)). This fact indicates that measurement of bearing temperatures at the inner-race bore and outer-race outside diameter does not reveal conditions within the bearing.

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Test 8. - Test 8 was conducted with bearing 12 (two-piece roller-riding bronze (brass) cage) with a syrup-bonded MoS_2 coating after liquid honing; the bearing was operated for 6 minutes at a DN value of 0.3×10^6 and a radial load of 368 pounds. No indication that the bearing would approach an equilibrium running temperature was apparent. No severe physical damage to the bearing was evident on post-test examination although some small amount of wear had occurred in the cage-locating pocket causing an increase in the cage diametral clearance.

Test 9. - Test 9 was conducted with bearing 13 (cageless), which had a syrup-bonded MoS_2 coating after liquid honing. The bearing, which was operated without outer-race snap rings, ran rough and very hot at a DN value of 0.375×10^6 and a radial load of 368 pounds. Although the bearing did not fail, no attempt was made to run at higher DN values because of excessively high operating temperatures. The maximum observed bearing temperature was 442° F. Wear was observable on the roller ends and on the flanges of the inner-race track (fig. 7(b)). The total running time was 3.2 hours.

Test 10. - Test 10 was conducted with bearing 14 (two-piece roller-riding bronze (brass) cage), which had a syrup-bonded MoS_2 coating. The bearing ran satisfactorily at a DN value of 0.3×10^6 and a radial load of 368 pounds but failed after running for 4 minutes at a DN of 0.375×10^6 and a load of 368 pounds. Cage wear resulted in the binding of the cage, which, in turn, caused the ejection of the cage cover-plate from the bearing. (This bearing had been disassembled for coating.) Total running time was 1.06 hours.

Test 11. - Test 11 was conducted with bearing 15 (cageless) lubricated by the MoS_2-air mist single-opposed-jet system. The bearing was MoS_2 syrup-bonded coated before operation. The bearing was operated without outer-race snap rings. Although operation was somewhat rough, and seemingly unstable with respect to operating temperature, no failure occurred at DN values up to and including 0.975×10^6 with a radial load of 368 pounds. Total running time was 11.8 hours. Bearing 15 was very sensitive to the amount of solid MoS_2 delivered to it per unit time. Because it was found impossible to keep the flow of MoS_2 constant at a constant air pressure owing to intermittent clogging in the supply tubes, the operating temperatures varied considerably at a specific DN value. At the conclusion of the test, the bearing diametral clearance had decreased from 0.0016 to 0.0015 (because of small MoS_2 build-up on the rollers). A photograph of bearing 15 after test 11 is shown in figure 7(c); no surface damage is evident. In addition, no measurable wear could be detected on any surfaces. Bearing 15 was the only MoS_2-air mist lubricated bearing to operate at very high speeds without showing wear or surface damage.

Test 12(a). - Test 12(a) was conducted with bearing 16 (one-piece inner-race-riding bronze (brass) cage) which was lubricated by the MoS_2-air mist single-opposed-jet system. The bearing operated to a DN of 0.675×10^6 with a radial load of 368 pounds. Again the operation was rough and unstable with respect to operating temperature but no failure occurred. Total running time of this test was 8.4 hours. 2257

Test 12(b). - Test 12(b) was conducted with bearing 16 (after conclusion of test 12(a)), which was lubricated by the MoS_2-air mist, modified-single-jet system (fig. 4(c)). The bearing was operated from a DN of 0.675×10^6 to a DN of 0.9×10^6 with a radial load of 368 pounds. Operation, although somewhat rough, was very stable with respect to operating temperature. Operating temperatures were considerably lower with the modified-single-jet system than with the single-opposed-jet system. The possibility that the air stream of the modified single jet promoted cooling was eliminated by completely shutting down the air stream for short periods of time. This produced no detectable rises in operating temperature. At the conclusion of the test, the mounted bearing diametral clearance had increased from 0.0005 to 0.0006 inch, whereas the cage diametral clearance had increased from 0.013 to 0.022 inch. The bearing was not run to failure, and it is shown in figure 7(d) (after test 12); there was little evidence of surface damage or wear except at the cage-loading surfaces. The running time of test 12(b) was 9.1 hours. The total running time on bearing 16 was 17.5 hours.

Test 13(a). - Test 13(a) was conducted with bearing 17 (cageless), which was lubricated with oil through a single 0.089-inch-diameter jet aimed perpendicularly to the bearing face and at the inner-race-flange outside diameter. The test bearing operated satisfactorily up to and including a DN of 1.2×10^6 with a radial load of 368 pounds. Total running time was 9.4 hours.

Test 13(b). - Test 13(b) was conducted without any lubrication of bearing 17 after the conclusion of test 13(a). The bearing operated satisfactorily at a DN of 0.3×10^6 for 1 hour and reached a temporary equilibrium temperature of 103° F for both the outer-race-maximum and inner-race temperatures. Then, without a change in speed, the bearing temperatures increased slowly until failure occurred 6 minutes after the temperature had begun to rise.

At the conclusion of the test the mounted bearing clearance had increased from 0.0007 to 0.0011 inch. Excessive wear occurred at the roller ends and at the guiding surfaces of the inner-race flanges.

<u>Comparison of high-speed lubricating techniques.</u> - The effects of DN value on the operating temperatures of bearings 13, 14, 15, and 16 are given in figure 8. These bearings were lubricated with MoS_2 syrup-bonded coatings, MoS_2-air mist, or by both methods. The bearing operating temperatures increased at a rate greater than linear with increasing DN value for all tests (fig. 8).

Comparison of tests 9 and 11 in figure 8 show that the MoS_2-air mist lubrication method is superior to the MoS_2 syrup-bonded coating for the cageless-type roller bearings because much lower operating temperatures and much higher operating speeds are possible with the MoS_2-air mist lubrication technique.

Comparison of tests 11 and 12(a) reveals that the MoS_2-air mist was more effective in lubricating bearing 15 (cageless) than in lubricating bearing 16 (one-piece inner-race riding bronze (brass) cage). This phenomenon may be attributed to (a) the cage acting as a barrier to the MoS_2-air mist and preventing its reaching the cage roller pockets and inner-race roller-guide flange surfaces in sufficient quantity; (b) MoS_2 being more effective in steel-to-steel lubrication than in bronze (brass)-to-steel lubrication. For example, at a DN of 0.6×10^6, the outer-race-maximum temperature of bearing 16 was 88° higher and the inner-race temperature 102° F higher than were the corresponding temperatures of bearing 15 for similar MoS_2-air mist lubricating techniques; this represents a significant difference in heat generation within the two bearing types.

Parts (a) and (b) of test 12 reveal the superiority of the MoS_2 modified-single-jet lubricating system over the MoS_2 single-opposed jet system. At a DN value of 0.675×10^6, the outer-race maximum temperatures with these two systems were 230° and 355° F, respectively, (fig. 8); in addition, the operating temperature was very stable with the modified-single-jet system.

For comparable bearings 15 and 13, or 16 and 10 (not shown in figure 8) comparison of the performance characteristics and the bearing appearance after runs shows that MoS_2-air mist provides lubrication that is somewhat effective in preventing wear and failure.

Comparison of tests 7, 8, 9, and 10 shows that, where lubrication is inadequate or nonexistent, the presence of a cage is apparently detrimental.

No definite conclusions can be made concerning the value of the MoS_2 syrup-bonded coating applied to bearings 12, 13, and 14 because of the incomplete nature of the tests. Although it has been shown that the existence of a syrup-bonded MoS_2 coating reduces the coefficient of sliding friction (reference 3), it was not successful in these tests. In all probability, the high sliding velocities encountered in high-speed roller bearings, together with the normal forces that exist between the sliding surfaces, considerably reduce the effective life of a MoS_2 syrup-bonded coating which is not continually reformed on the sliding surfaces.

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Comparison of operating temperatures for oil lubrication and for MoS_2-air mist lubrication. - The operating temperatures of bearings 6, 15, 16, and 17 are plotted against DN in figure 9. Bearings 15 and 16 were MoS_2-air mist lubricated. The curve shown for bearing 16 is that obtained with the MoS_2-air mist modified-single-jet lubrication method. The curve of bearing 6 is for an oil lubricated one-piece inner-race-riding cage-type bearing and was obtained from reference 4. The conditions of operation for this bearing were: load, 368 pounds; oil inlet temperature, 100° F; oil-jet diameter, 0.089 inch; and oil flow, 2.75 pounds per minute. The oil used was the same as shown in figure 6. The curve for bearing 17 is for an oil-lubricated full-complement bearing (cageless). The conditions of operation and lubrication for this bearing were the same as those for bearing 6.

Both types of bearing give approximately the same relative performance with regard to operating temperature (fig. 9) when comparison is made of the data of the oil-lubricated tests and of the MoS_2-air mist lubricated tests; that is, bearing temperatures increased approximately linearly with increase in DN for bearings lubricated with oil through a single jet and bearing temperatures increased at a rate greater than linear with an increase in DN for bearings lubricated with MoS_2-air mist. Also, both types of bearing operated at higher temperature levels when lubricated with MoS_2-air mist than when lubricated with oil for all DN values. In general, the spread in the operating temperatures increased with an increase in DN. At DN values of 0.3×10^6 to 0.7×10^6 the difference in outer-race-maximum temperatures was approximately 60° F and the difference in inner-race temperatures was approximately 100° F for the two lubricating methods. At a DN of 0.975×10^6, the spread in the outer-race-maximum temperatures was approximately 160° and the spread in inner-race temperatures was approximately 170° F for the two lubricating methods. With oil lubrication the oil (2.75 lb/min) acts as a coolant as well as a lubricant, whereas with the MoS_2-air mist lubrication no appreciable cooling occurs because of the lubricant source. (The felt shaft seal was not used in the oil lubricated runs.)

<u>Bearing-operating temperature above ambient-air temperature.</u> - The outer-race-maximum and inner-race operating temperatures above ambient-2257 air temperature in the test rig are plotted against DN in figure 10, for bearings 13, 14, 15, and 16 and in figure 11 for bearings 6, 15, 16, and 17.

The value of T_B-T_{AA} (bearing temperature minus ambient-air temperature) increases at a rate greater than linear with an increase in DN for the syrup-bonded MoS_2 lubricated bearings as well as for the MoS_2-air mist lubricated bearings. This rapid increase is to be expected because the ambient-air temperature in the test rig is a function of the test-bearing operating temperature (figs. 8 and 9). In contrast is the almost linear increase in T_B-T_{AA} for the oil lubricated bearings (6 and 17). (In reference 5, it is shown that when bearing temperature increases linearly with an increase in DN value, T_{AA} increases linearly with an increase in DN.) The bearing operating temperature is dependent on the air temperature surrounding the bearing. This dependence is greater when no lubricant cooling occurs for the syrup-bonded MoS_2 and MoS_2-air mist lubricated bearings as compared with oil-lubricated bearings where the lubricant removes a significant amount of heat from the bearing in addition to performing the lubricating function. It may be seen in figure 10 that the MoS_2-air mist lubricated cageless roller bearing operates at a lower T_B-T_{AA} and, therefore, possibly generates less heat than any of the other bearings shown in figure 10. It is impossible to verify this fact inasmuch as friction torque readings of the bearing were not made. Also, this fact is not revealed in figure 8 where the data of tests 11 and 12(b) are more nearly coincident. Also, over the range of DN values from 0.45×10^6 to 0.85×10^6 the MoS_2-air mist-lubricated cageless bearing operated at lower outer-race T_B-T_{AA} than did the oil lubricated cage-type bearing (fig. 11). Inasmuch as the inner-race T_B-T_{AA} for the MoS_2-air mist-lubricated bearing was somewhat higher than for the oil-lubricated cageless bearing, it cannot be postulated at this time that the heat generated was less for the MoS_2-air mist-lubricated cageless bearing. This discussion (although not including the effects of heat generation by the shaft seal) serves to further illustrate the possible advantages of MoS_2-air mist lubrication.

SUMMARY OF RESULTS

A preliminary investigation of the effectiveness of molybdenum disulfide MoS_2 as a bearing lubricant at high temperatures, and at high speeds was conducted.

The following results were obtained in the high-temperature evaluation of bearings, which was conducted with 1-inch-bore ball bearings equipped with two-piece stamped and riveted steel cages at ambient temperatures from room temperature to 1000° F, bearing DN (product of bearing bore in mm times shaft speed in rpm) values of 0.04×10^6 and 0.09×10^6, a thrust load of 20 pounds, and lubrication by MoS_2-air mist at the rate of 0.35 to 0.7 ounce per hour: 2257

1. A 1-inch bore ball bearing operated satisfactorily for 6 hours when lubricated only by a MoS_2-air mist at a shaft speed of 1725 rpm, a thrust load of 20 pounds, and at an ambient temperature which was progressively increased in 200° F increments from 400° to 800° F. The bearing failed, however, when the temperature was subsequently increased to 1000° F. In a duplicate test, a second bearing ran successfully for 1 hour at 1000° F for a total running time of 8.4 hours at which time the test was terminated for inspection of the bearing. The bearing surface was badly oxidized.

2. At an ambient temperature of 800° F, a speed of 3400 rpm (DN, 0.09×10^6), and a thrust load of 20 pounds, an uncoated dry bearing had a life of 6 minutes, whereas a MoS_2-air mist-lubricated bearing had a life of 71 minutes.

3. A coating of ferroso ferric oxide Fe_3O_4 on a bearing run without any lubrication at room temperature, 1725 rpm, and 20 pounds thrust load did not result in any improvement in operating performance over that of an uncoated dry bearing.

The following results were obtained in the high-speed evaluation, which was conducted in a radial load rig with 75-millimeter-bore (size 215) cylindrical-roller bearings of three designs at DN values of 0.3×10^6 to 0.975×10^6, a radial load of 368 pounds, and with three methods of lubrication as well as dry operation:

1. A size 215 cylindrical, cageless-roller bearing provided with a MoS_2-syrup coating before operation and lubricated only with a MoS_2-air mist during operation, ran satisfactorily in a test of 11.8 hours duration without showing signs of wear or surface damage.

The run was conducted at a load of 368 pounds and at DN values which were increased progressively from 0.3×10^6 to 0.975×10^6 (13,000 rpm). The maximum bearing temperature was 386° F.

Roller-riding and inner-race-riding bronze (brass) cage-type bearings when subjected to similar conditions indicated a lower limiting DN value than the cageless type bearings and showed signs of considerable wear.

2. The modified-single-jet lubricating system was superior to the single-opposed-jet system inasmuch as the modified system provided more adequate control of the flow rate of MoS_2, which resulted in lower bearing operating temperatures.

3. A syrup-bonded coating of MoS_2 over both untreated and liquid-honed surfaces was an inadequate bearing lubricant under the operating conditions investigated.

4. Operation without lubrication of a one-piece inner-race-riding cage-type bearing resulted in excessive cage wear in the roller pockets and in a multiple fracture of the cage which caused failure after 9 minutes at a DN value of 0.45×10^6 after running for about 1 hour at DN values of 0.3×10^6 and 0.375×10^6. Similar operation of a cageless-type bearing resulted in excessive wear at the roller ends and inner-race flange guiding surfaces, which caused bearing failure after running for 1 hour and 6 minutes at a DN value of 0.3×10^6.

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Cleveland, Ohio

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2. Singleterry, C. C.: Synthethic Lubricants for Military Aircraft. Symposium on Synthetic Lubricants. Spec. Tech. Pub. 77, A.S.T.M., June 16-20, 1947, pp. 26-30.

3. Johnson, Robert L., Godfrey, Douglas, and Bisson, Edmond E.: Friction of Solid Films on Steel at High Sliding Velocities. NACA TN 1578, 1948.

4. Macks, E. Fred, and Nemeth, Zolton N.: Investigation of 75-Millimeter-Bore Cylindrical Roller Bearings at High Speeds. I - Initial Studies. NACA TN 2128, 1950.

5. Macks, E. Fred, and Nemeth, Zolton N.: Investigation of 75-Millimeter-Bore Cylindrical Roller Bearings at High Speeds. III - Lubrication and Cooling Studies - Oil Inlet Distribution, Oil Inlet Temperature, and Generalized Single-Oil-Jet Cooling - Correlation Analysis. NACA TN 2420, 1951.

6. Norman, T. E.: Molybdenite as a Die Lubricant. Metal Progress, vol. 50, no. 2, August 1946, p. 314.

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TABLE I - PARTICLE SIZE OF MOLYBDENUM DISULFIDE[a]

Particle size	Weight (percent)
Over 200 mesh	1
Under 200 mesh over 400 mesh	10
Under 400 mesh over 22 microns	30
Under 22 microns over 11 microns	27
Under 11 microns over 5 microns	15
Under 5 microns	17

[a]Purified molybdenum disulfide, 99.9 percent. Impurity mainly iron oxide

TABLE II - HIGH TEMPERATURE RESULTS

Test number	1	2	3	4	5	6
Bearing number	501	502	503	504	505	506
Construction	Ball; stamped and riveted steel cage	Ball; stamped and riveted steel cage	Ball; stamped and riveted steel cage	Ball; stamped and riveted steel cage	Ball; stamped and riveted steel cage	Ball; stamped and riveted steel cage
Bearing grade	3	3	3	3	3	3
Number of balls	10	10	10	10	10	10
Diameter of balls, (in.)	0.250	0.250	0.250	0.250	0.250	0.250
Pitch diameter of bearing, (in.)	1.417	1.417	1.417	1.417	1.417	1.417
Unmounted bearing: Diametral clearance of bearing, (in.)	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
Diametral clearance of cage, (in.)	[a]0.016	[a]0.016	[a]0.016	[a]0.016	[a]0.016	[a]0.016
Mounted bearing: Diametral clearance of bearing, (in.)	[a]0.0001	[a]0.0001	[a]0.0001	[a]0.0001	[a]0.0001	[a]0.0001
Bearing coating	Fe_3O_4	None	Fe_3O_4	None	None	None
Type of lubrication	Dry	Dry	MoS_2-air mist	MoS_2-air mist	Dry	MoS_2-air mist
MoS_2 flow rate approximate, (oz/hr)	0	0	0.35-0.7	0.35-0.7	0	0.35-0.7
Lubricant-air pressure (in. hg)	0	0	0.3-0.8	0.3-0.8	0	0.3-0.8
Thrust load, (lb)	20	20	20	20	20	20
Speed, (rpm)	1725	1725	1725	1725	3400	3400
Maximum successful operating temperature, ±40° F	Room temperature	Room temperature	800	1000	----	----
Total running time, (hr)	1.32	2.45	6.00	8.37	0.10	1.18
[b]ΣA temperature, (°F) × time (min)	----	22.5×10^3	206×10^3	323×10^3	4.45×10^3	45.8×10^3
Remarks	Failure; cage broken	Failure; cage broken	Failure occurred as temperature was being increased from 800° F to 1000° F, outer race rotated.	No failure. Unmounted bearing diametral clearance increased to 0.0007 inch; cage clearance increased so that cage rode on outer race.	Failure; cage broken in several places. No diametral clearance left in bearing.	Failure; cage broken. No diametral clearance left in either bearing or cage.

[a]Measurements obtained from sample bearing.

[b]Severity factor, (summation of products of difference between equilibrium bearing temperature and lubricant inlet temperature for each operating condition and corresponding operating time in minutes at that particular condition).

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TABLE III - HIGH-SPEED

NACA

Test number	7		8		9		10	
Bearing number	10		12		13		14	
Construction	One-piece inner-race-riding brass cage		Two-piece roller-riding brass cage		Cageless		Two-piece roller-riding cage	
Pitch diameter of bearing, (in.)	4.036		4.032		4.033		4.032	
Number of rollers	18		17		21		17	
	Before	After	Before	After	Before	After	Before	After
Roller diameter, (in.)	[a]0.5513	[b]0.5521	[a]0.5255	[c]0.5259	[a]0.5635	0.5638	[a]0.5255	[b]0.5263
Roller length, (in.)	[a]0.5510	0.5513	[a]0.6500	0.6503	[a]0.5625	0.5610 to .5673	[a]0.6500	0.6493
Unmounted bearing: [d]Diametral clearance Bearing	0.0018	[e]0.0000	0.0005	0.0013	0.0023 to .0027	0.005	0.0026	[e]0.0000
Cage	.013	Cage failure	.025 to .042	.028 to .046	Cageless	Cageless	.020 to .046	Cage failure
[g]Eccentricity	0.0001	--------	0.0000	0.0003	0.0001	0.0005	0.0000	--------
Mounted bearing: [h]Diametral clearance Bearing	0.0007	[e]0.0000	[i]0.0000	[i]0.0000	0.0012	0.0054	0.0010	[e]0.0000
Cage	.013	Cage failure	.025 to .042	.028 to .047	Cageless	Cageless	.020 to .046	Cage failure
Bearing surface treatment	None		Liquid honed		Liquid honed		None	
Bearing coating	None		MoS_2 Syrup bonded		MoS_2 Syrup bonded		MoS_2 Syrup bonded	
Type of lubrication	Dry		Dry		Dry		Dry	
Lubricant flow rate approximate, (oz/hr)	0		0		0		0	
Lubricant-air pressure (in. hg)	0		0		0		0	
Radial load, (lb)	368		368		368		368	
Maximum successful operating speed (rpm)	5000		----		5000		4000	
Maximum successful operating speed ($DN \times 10^{-6}$)	0.375		----		0.375		0.30	
Total running time, (hr)	2.2		0.1		3.2		1.06	
[j]$\Sigma\Delta$ temperature (°F) x time (min.)	10.8×10^3		0.53×10^3		34.2×10^3		5.95×10^3	
Remarks	Failure due to multiple fracture of cage. Excessive brass pickup by rollers.		Bearing ran very hot without showing signs of reaching an equilibrium temperature.		Bearing ran rough and very hot. Wear on roller ends and inner-race flanges. No failure.		Failure due to cage wear. Excessive brass pickup by rollers, cage ejected.	

[a]Measurements obtained from sample bearing.
[b]Increase in roller diameter is due to brass pickup.
[c]Increase in roller diameter is due to MoS_2 syrup-bonded coating.
[d]Measurement obtained in fixture with dial gage.
[e]Due to excessive brass pickup by rollers.
[f]Diametral clearance actually decreased because of apparent growth of inner race at operating temperatures above 400° F.
[g]Measurement obtained in fixture with dial gage, inner race rotating and outer race stationary.
[h]Measurements obtained in test rig with dial gage.
[i]Due to MoS_2 syrup-bonded coating.
[j]Severity factor, summation of products of difference between equilibrium bearing temperature and lubricant inlet temperature for each operating condition and corresponding operating time in minutes at that particular condition.

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BEARING RESULTS

11		12(a)		12(b)		13(a)		13(b)	
15		16		16		17		17	
Cageless		One-piece inner-race-riding brass cage		One-piece inner-race-riding brass cage		Cageless		Cageless	
4.033		4.036		4.036		4.033		4.033	
21		18		18		21		21	
Before	After	Before	After	Before	After	Before	After	Before	After
[a]0.5635	0.5630	[a]0.5513	------	------	[a]0.5510	0.5635	------	------	[b]0.5632
[a]0.5625	0.5622	[a]0.5510	------	------	[a]0.5510	0.5625	------	------	0.5624
0.0026 Cageless	0.0028 Cageless	0.0020 .015	------ ------	------ ------	[f]0.0016 .021 to .022	0.0017 Cageless	------ ------	------ ------	0.0022 Cageless
0.0000	0.0010	0.0001 to .0002	------	------	0.0004	0.0001	------	------	------
0.0016 Cageless	0.0015 Cageless	0.0005 .015	------ ------	------ ------	0.0006 .021 to .022	0.0007 Cageless	------ ------	------ ------	0.0011 Cageless
None		None		None		None		None	
MoS_2 Syrup bonded		None		None		None		None	
MoS_2-air mist; single-opposed jets		MoS_2-air mist; single-opposed jets		MoS_2-air mist; modified single jet		Oil jet		Dry	
0 to 1.6		0 to 1.6		0 to 1.6		2.75 (lb/min)		0	
0 to 4.0		0 to 4.0		0 to 12.0		0		0	
368		368		368		0 to 1113		368	
13,000		8000		12,000		16,000		≈4000	
0.975		0.675		0.90		1.20		0.30	
11.8		8.4		9.1		9.4		1.1	
154×10^3		----		226.5×10^3		----		81.5×10^3	
Bearing ran rough and hot but no failure; no appreciable wear on any surface.		Bearing ran satisfactorily, but rough and unstable as regards operating temperature.		Run after conclusion of 12(a). Operation somewhat rough but stable as regards operating temperature. Steel surfaces discolored (dark blue) from heat but no appreciable wear. Wear on cage-locating surfaces but no failure.		Satisfactory operation.		Run after conclusion of 13(a). Bearing failed; damage to roller ends and inner-race guide flanges.	

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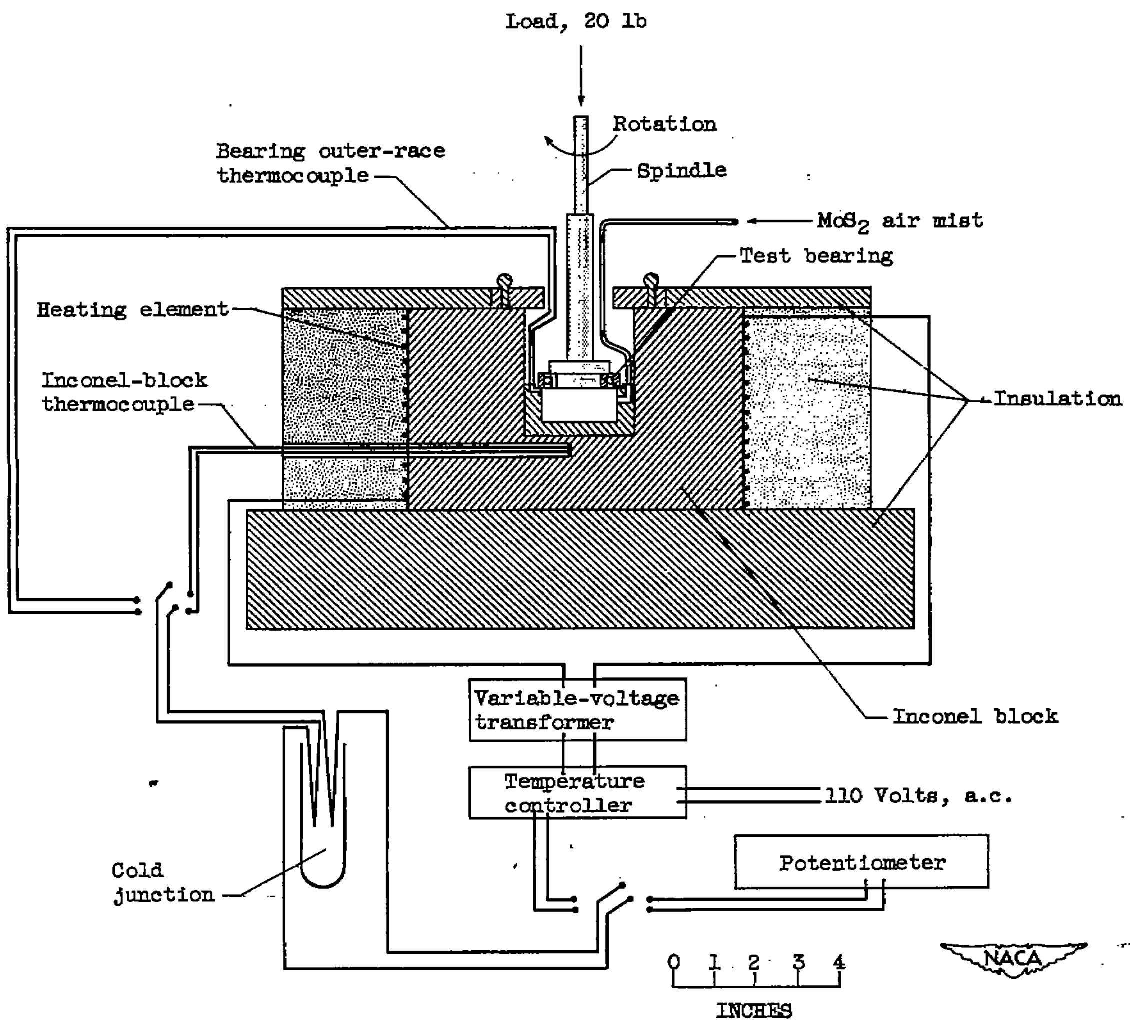

(a) Sketch showing instrumentation.

Figure 1. - High-temperature rig.

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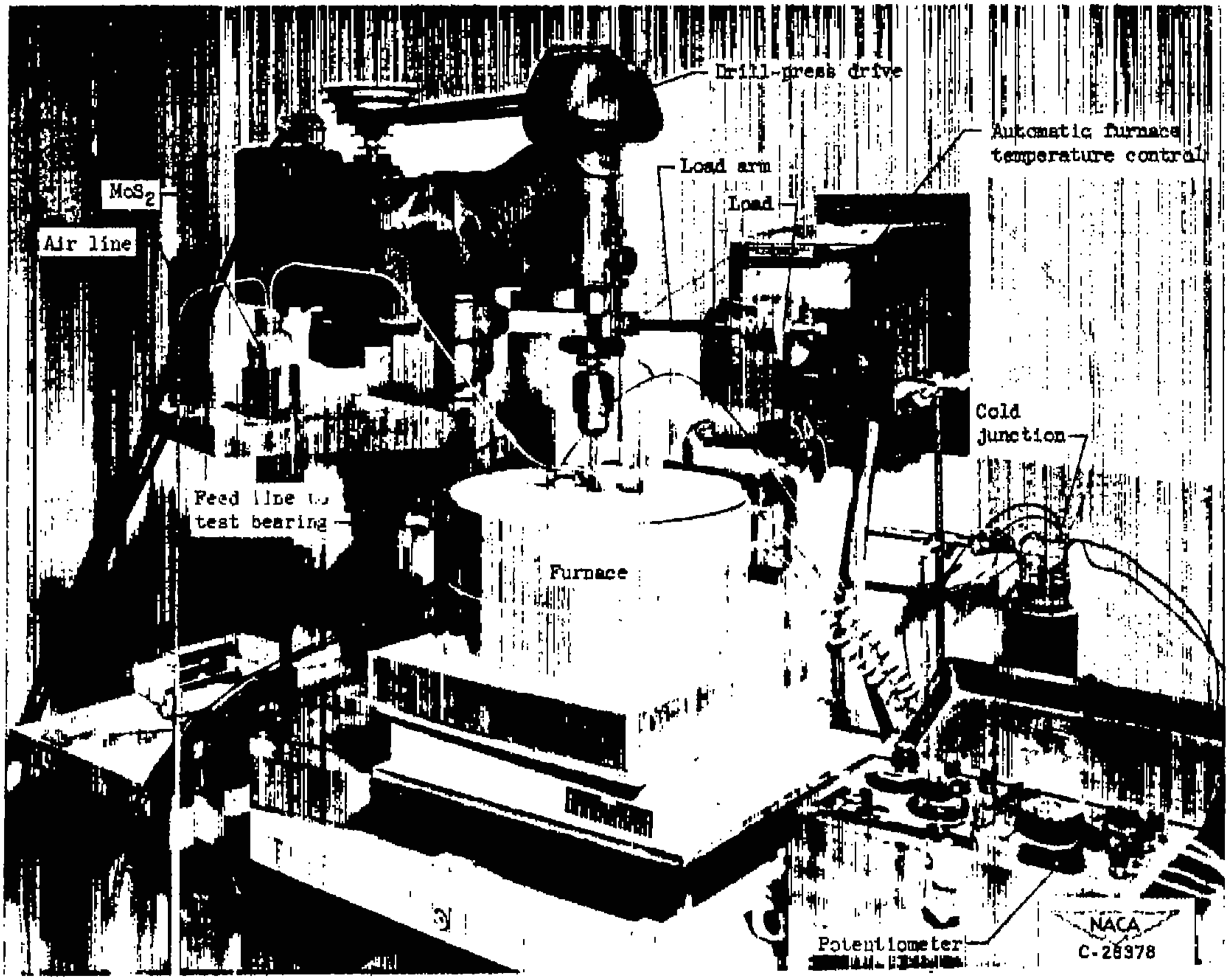

(b) Over-all view.

Figure 1. - Concluded. High-temperature rig.

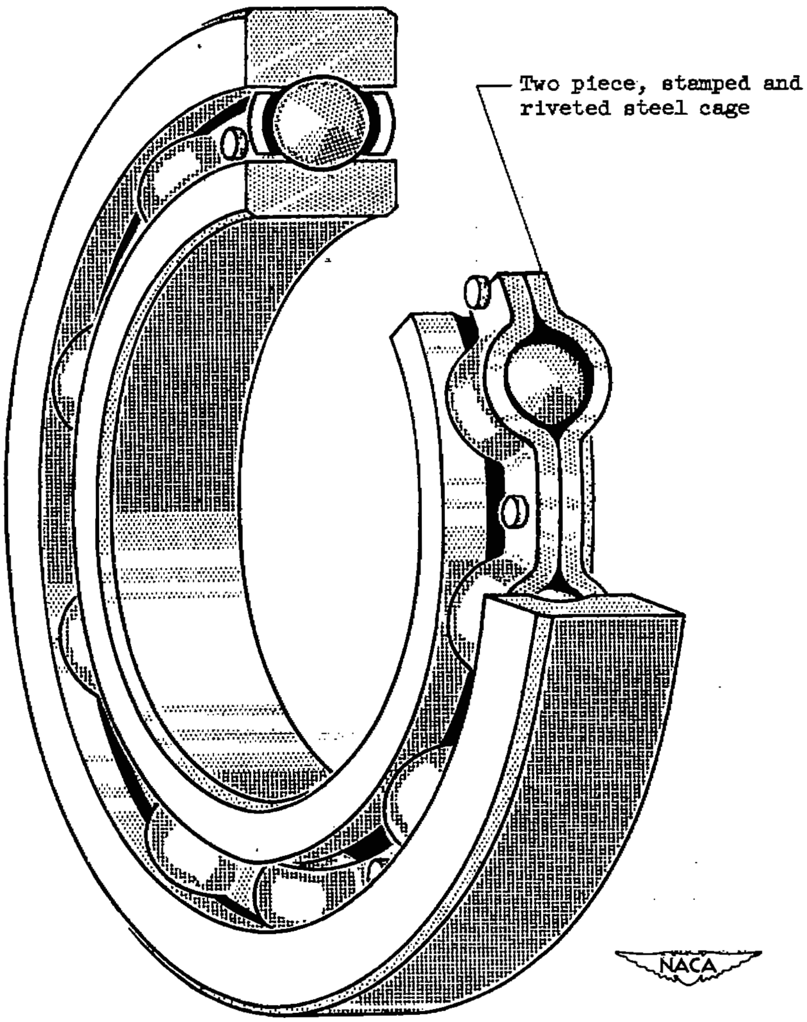

Figure 2. - High-temperature-rig test bearing.

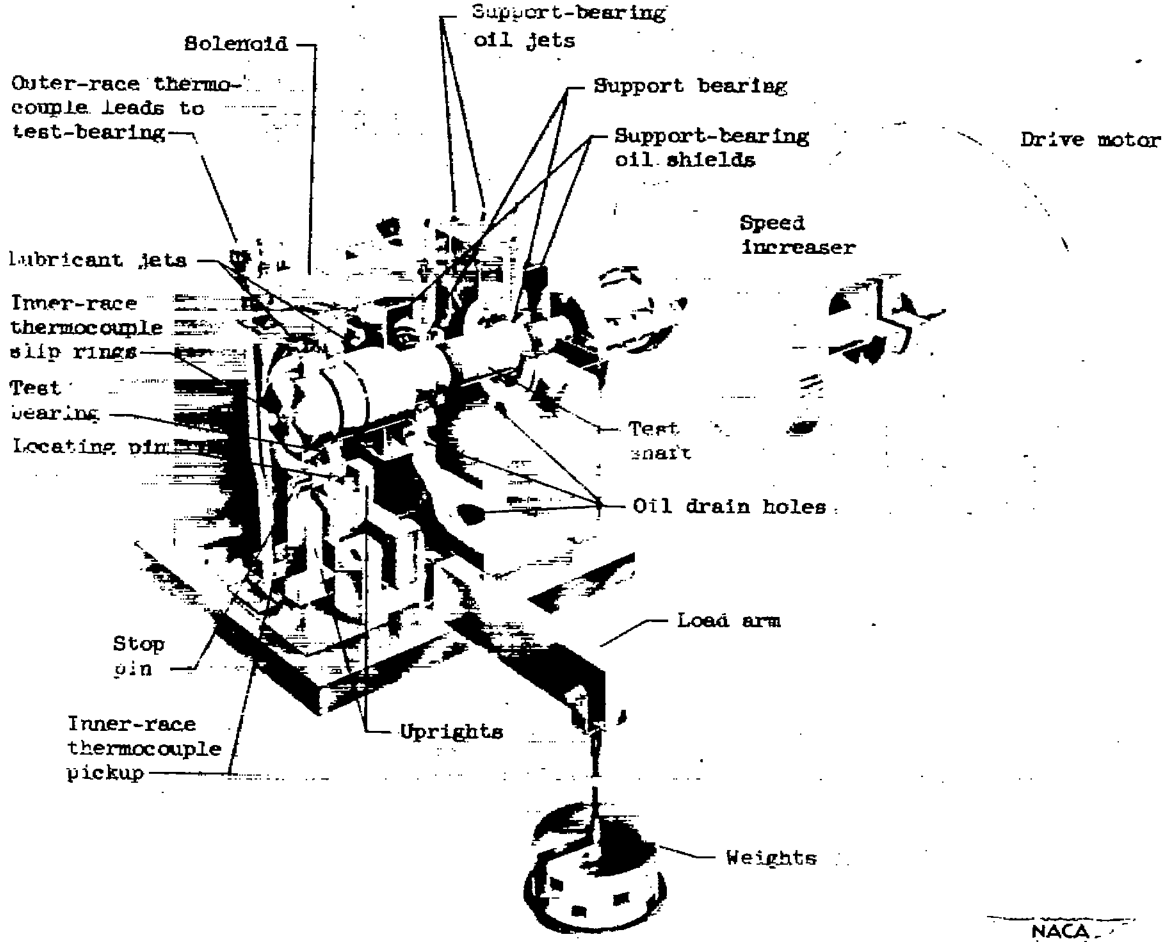

Figure 3. - Cutaway view of high-speed bearing rig.

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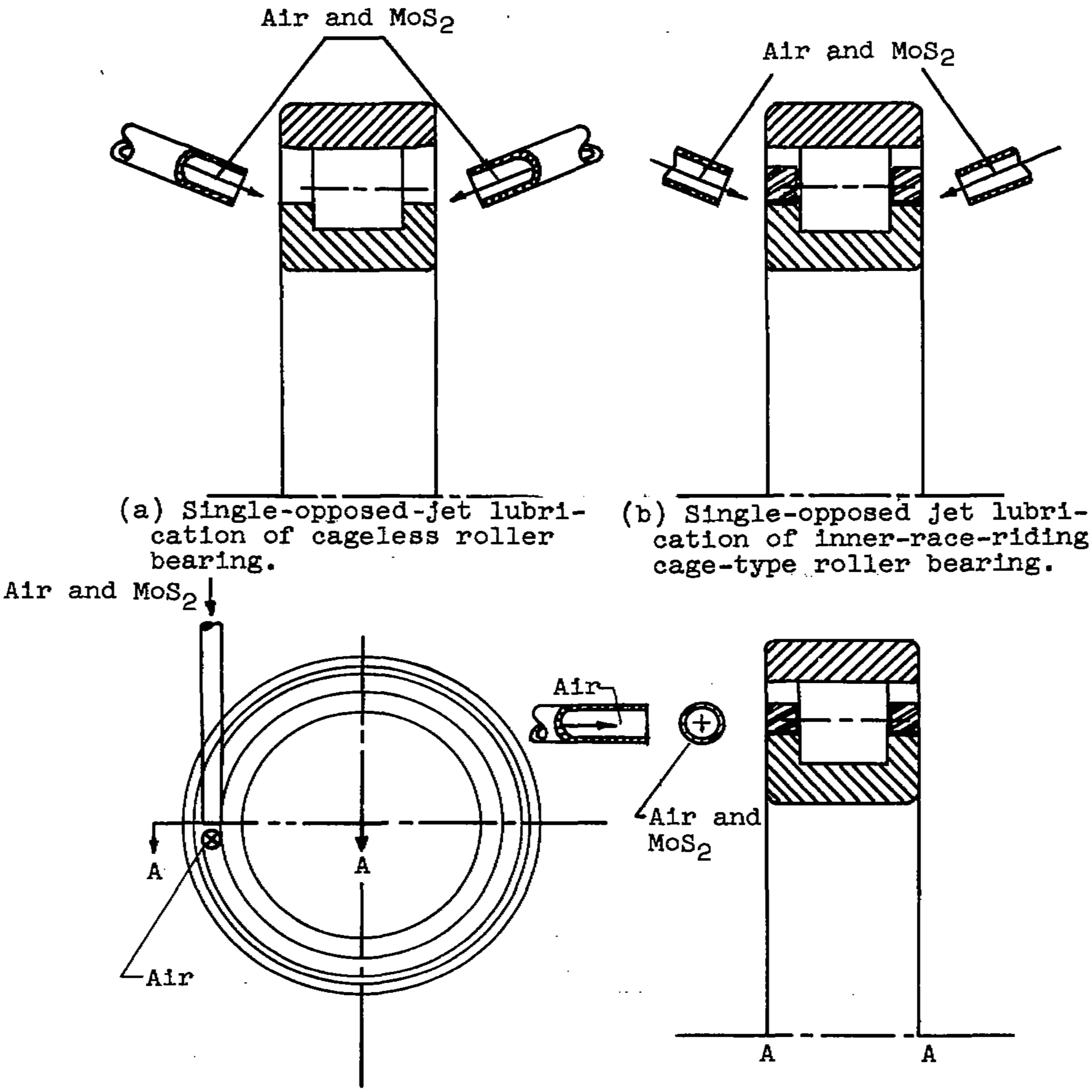
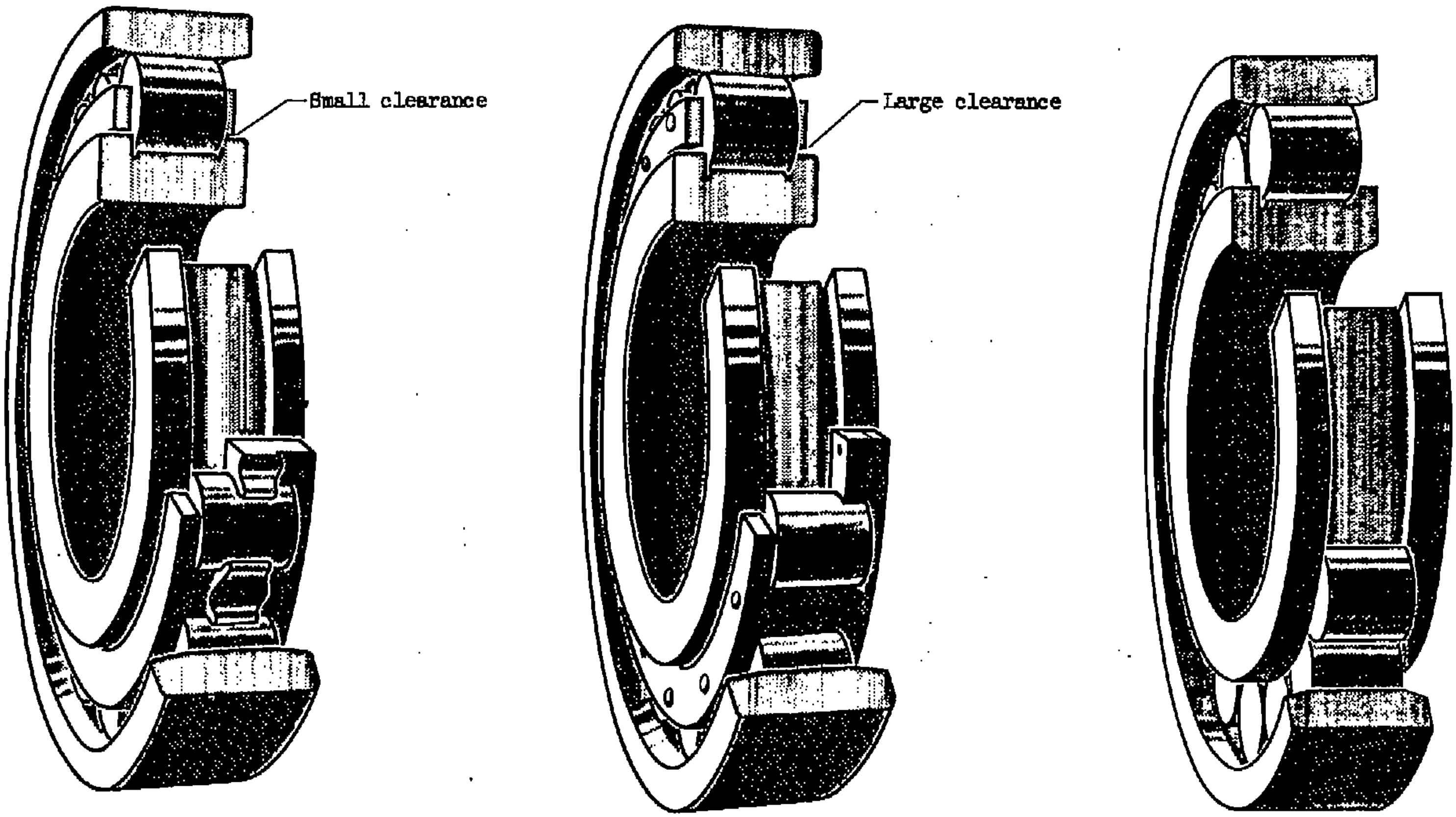


(a) Single-opposed-jet lubrication of cageless roller bearing.

(b) Single-opposed jet lubrication of inner-race-riding cage-type roller bearing.

(c) Modified-single-jet lubrication of inner-race-riding cage-type roller bearing.

Figure 4. - Molybdenum disulfide - air mist lubrication techniques.



(a) One-piece inner-race-riding cage.

(b) Two-piece riveted roller-riding cage.

(c) Full complement (cageless).

Figure 5. - High-speed-rig test bearings.

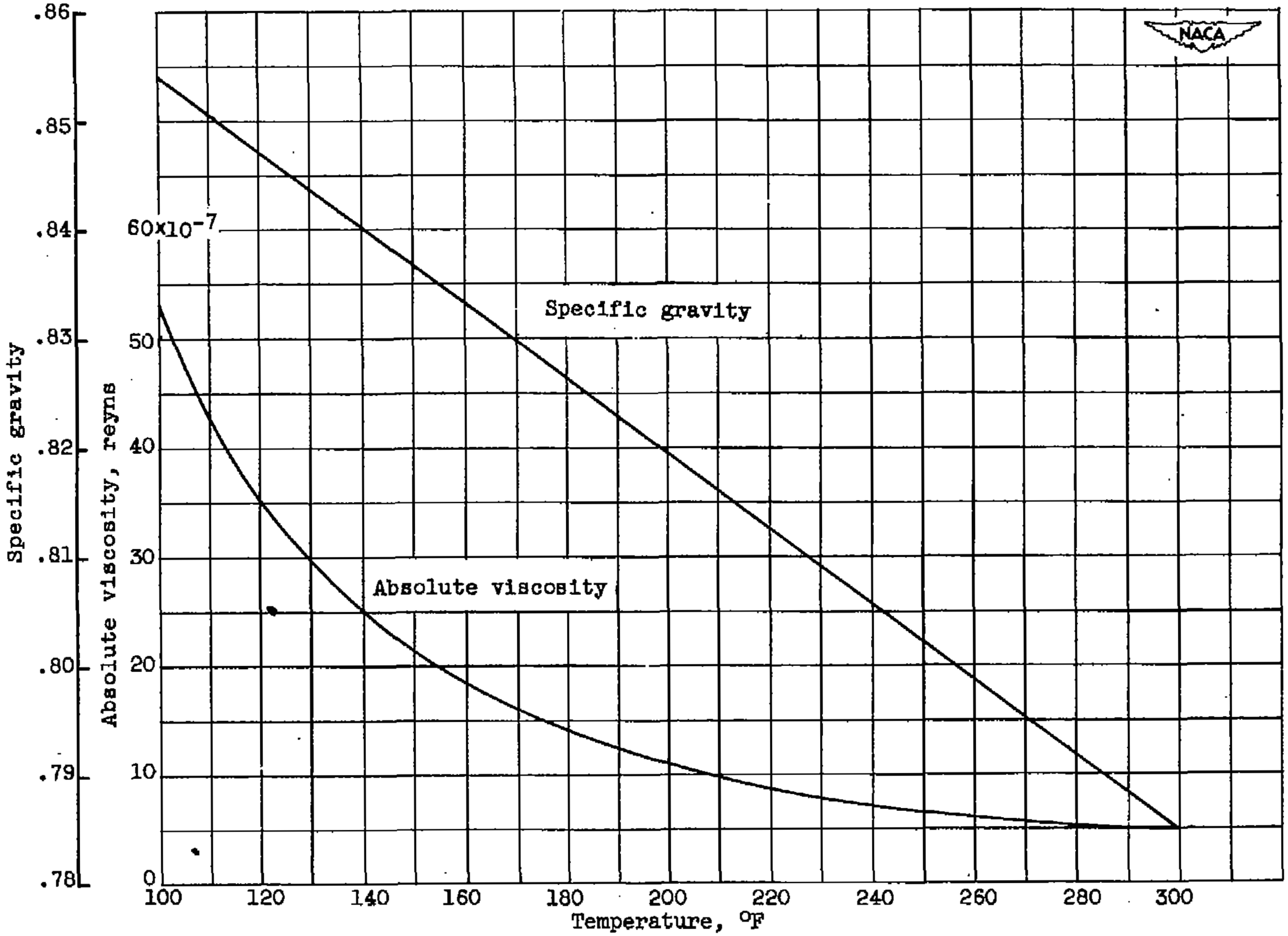
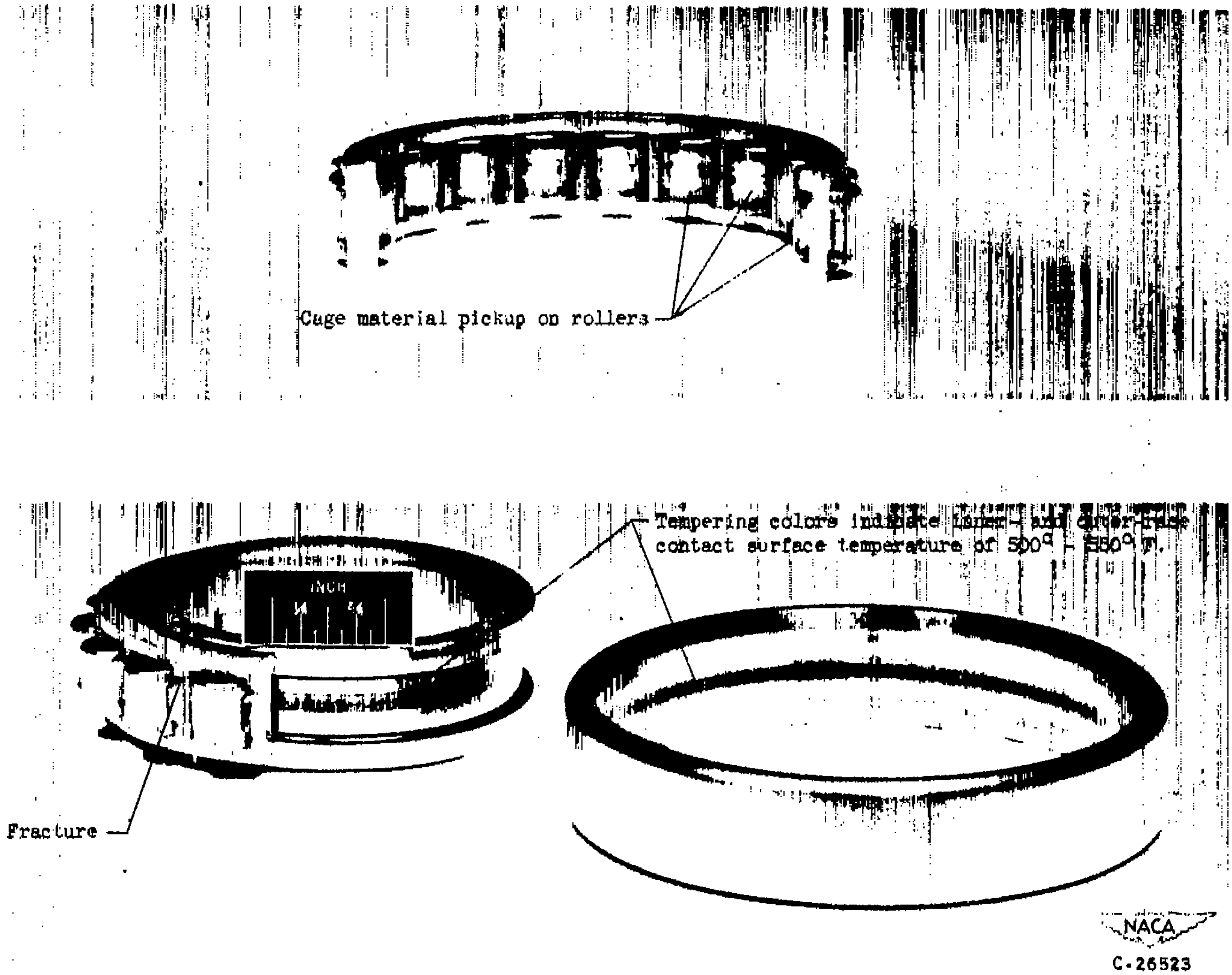
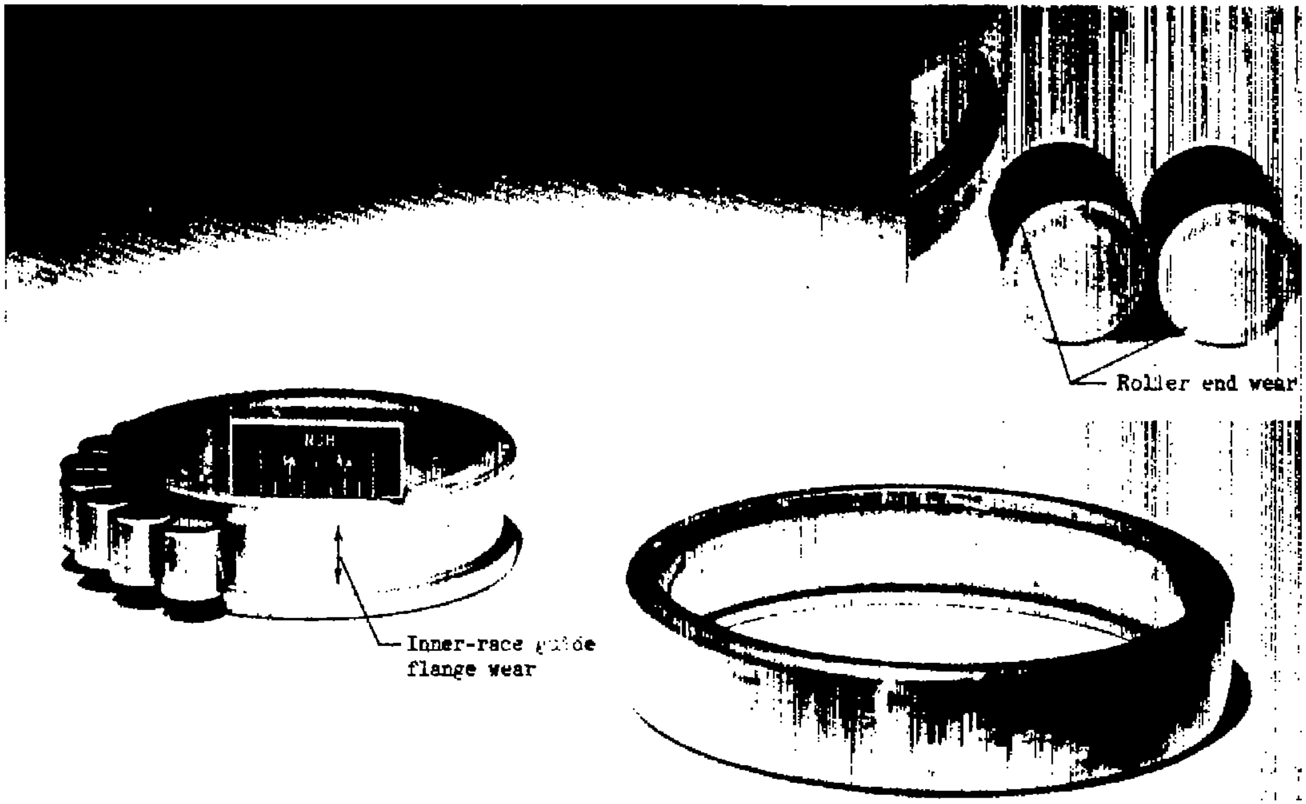


Figure 6. - Absolute viscosity and specific gravity of lubricant. Pour point, -50° F; flash point, 310° F; viscosity index, 150.



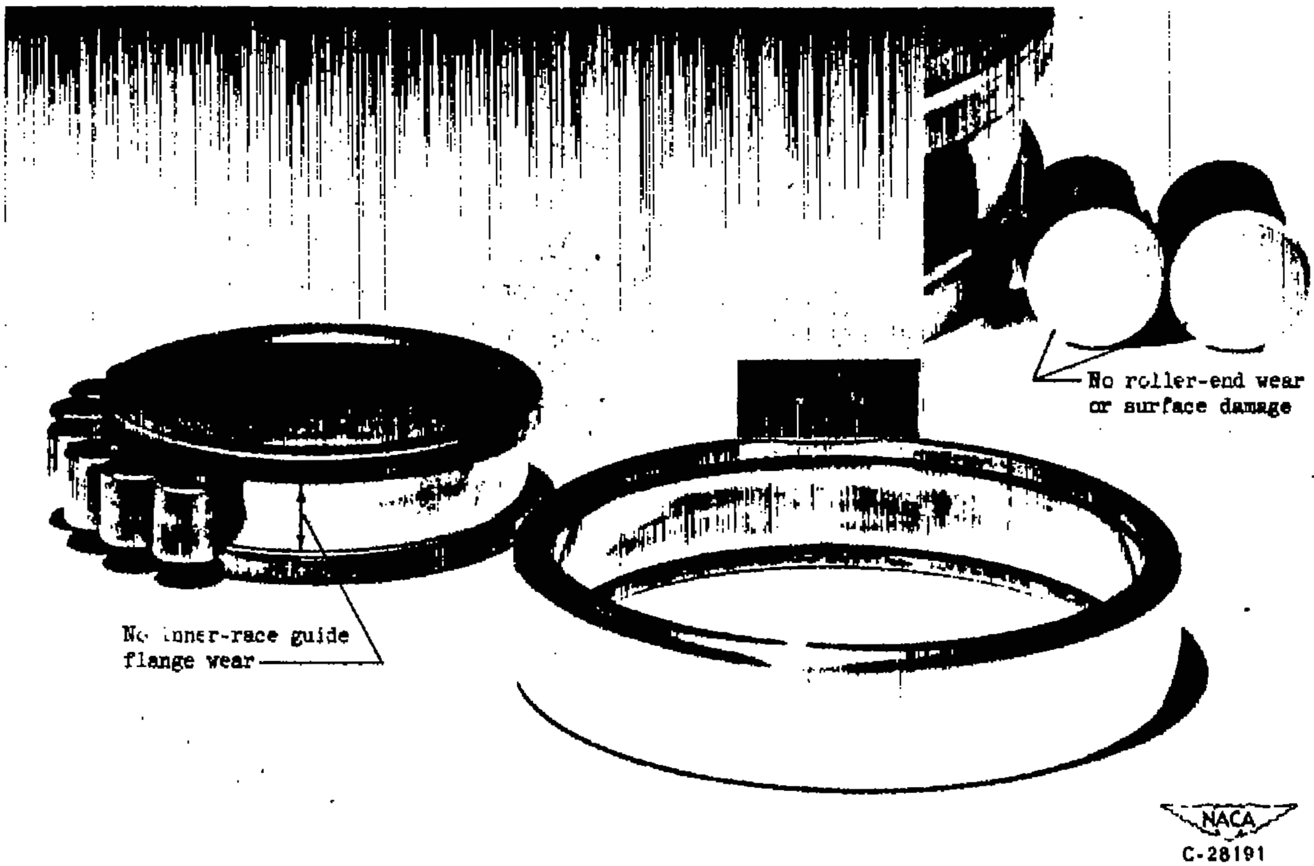
(a) Bearing 10.

Figure 7. - Condition of bearings after operation.



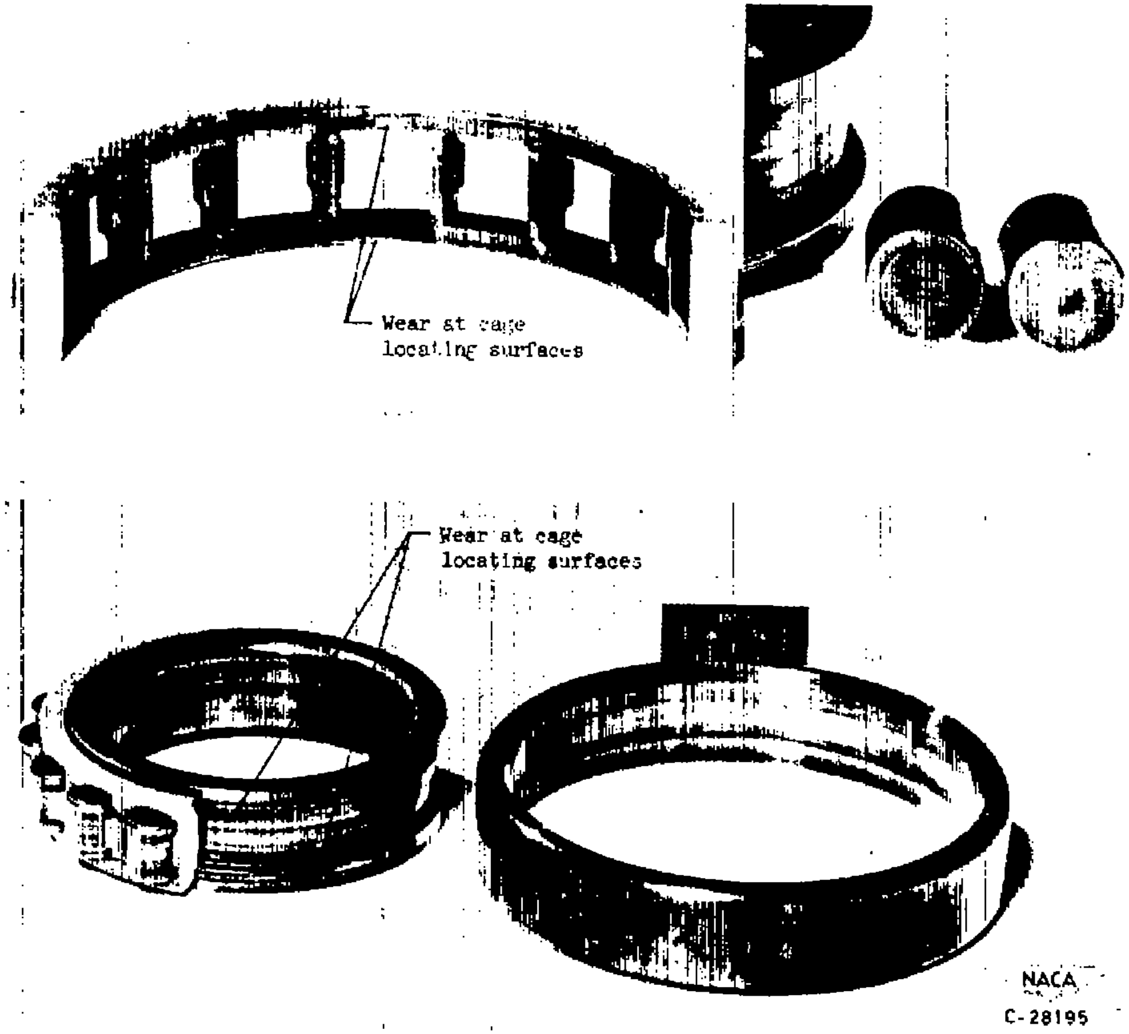
(b) Bearing 13.

Figure 7. - Continued. Condition of bearings after operation.



(c) Bearing 15.

Figure 7. - Continued. Condition of bearings after operation.



(d) Bearing 16.

Figure 7. - Concluded. Condition of bearings after operation.

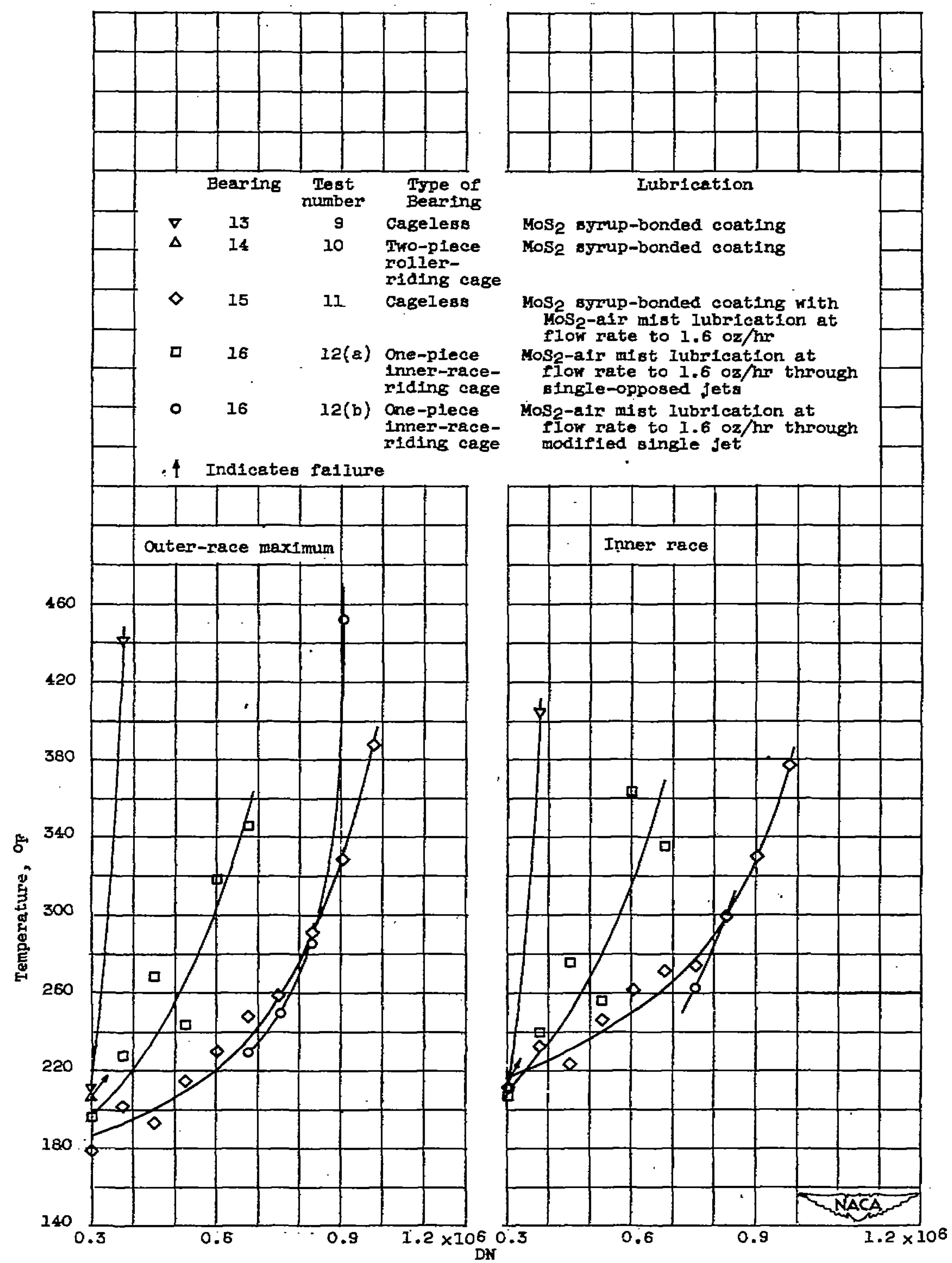


Figure 8. - Effect of DN on outer-race-maximum and inner-race temperatures of bearings 13, 14, 15, and 16 (all with shaft seal). DN, 0.3×10^6 to 0.975×10^6; load; 368 pounds.

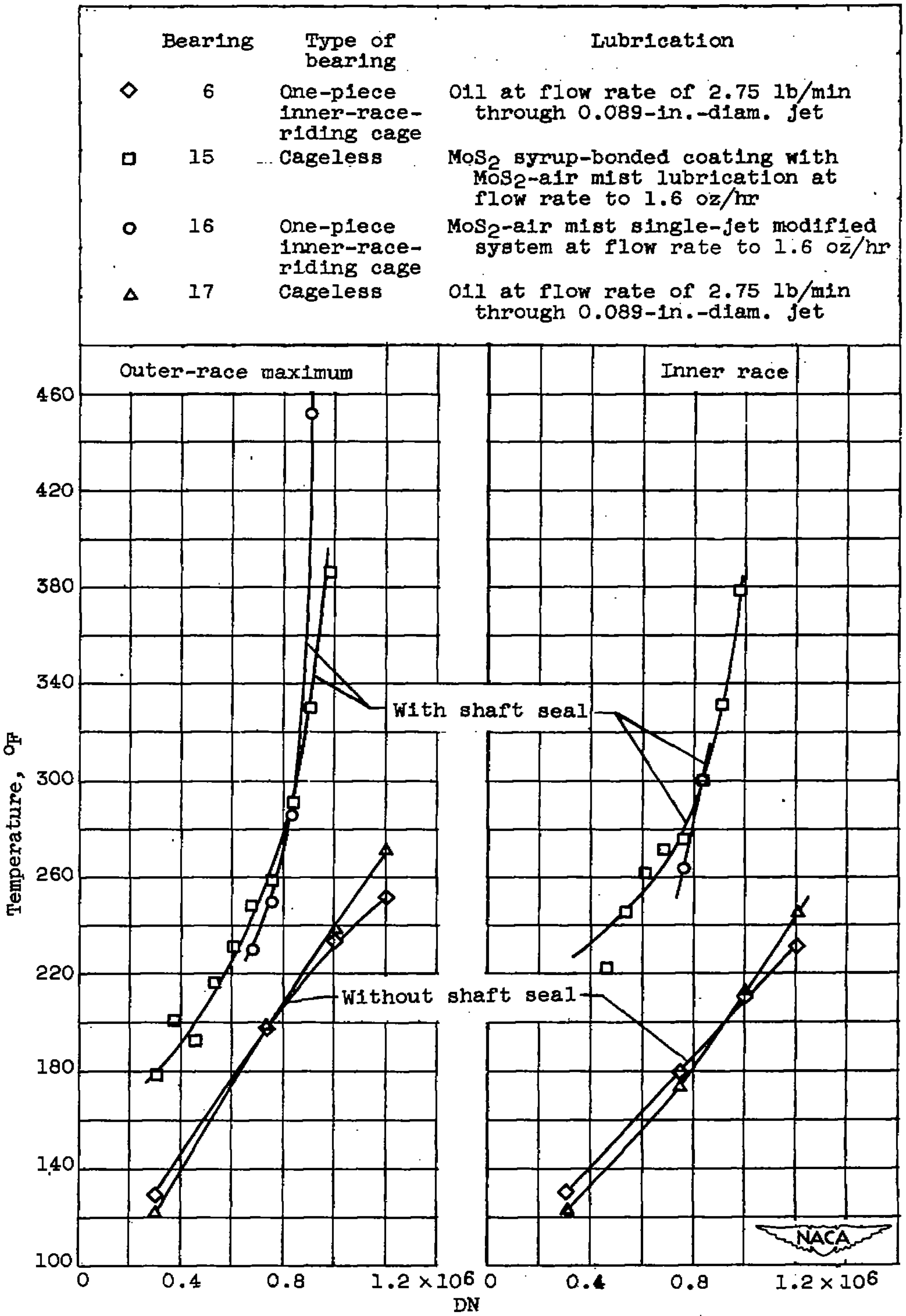


Figure 9. - Effect of DN on outer-race-maximum and inner-race temperatures of bearings 6 (reference 4), 15, 16, and 17. DN, 0.3×10^6 to 1.2×10^6; load, 368 pounds.

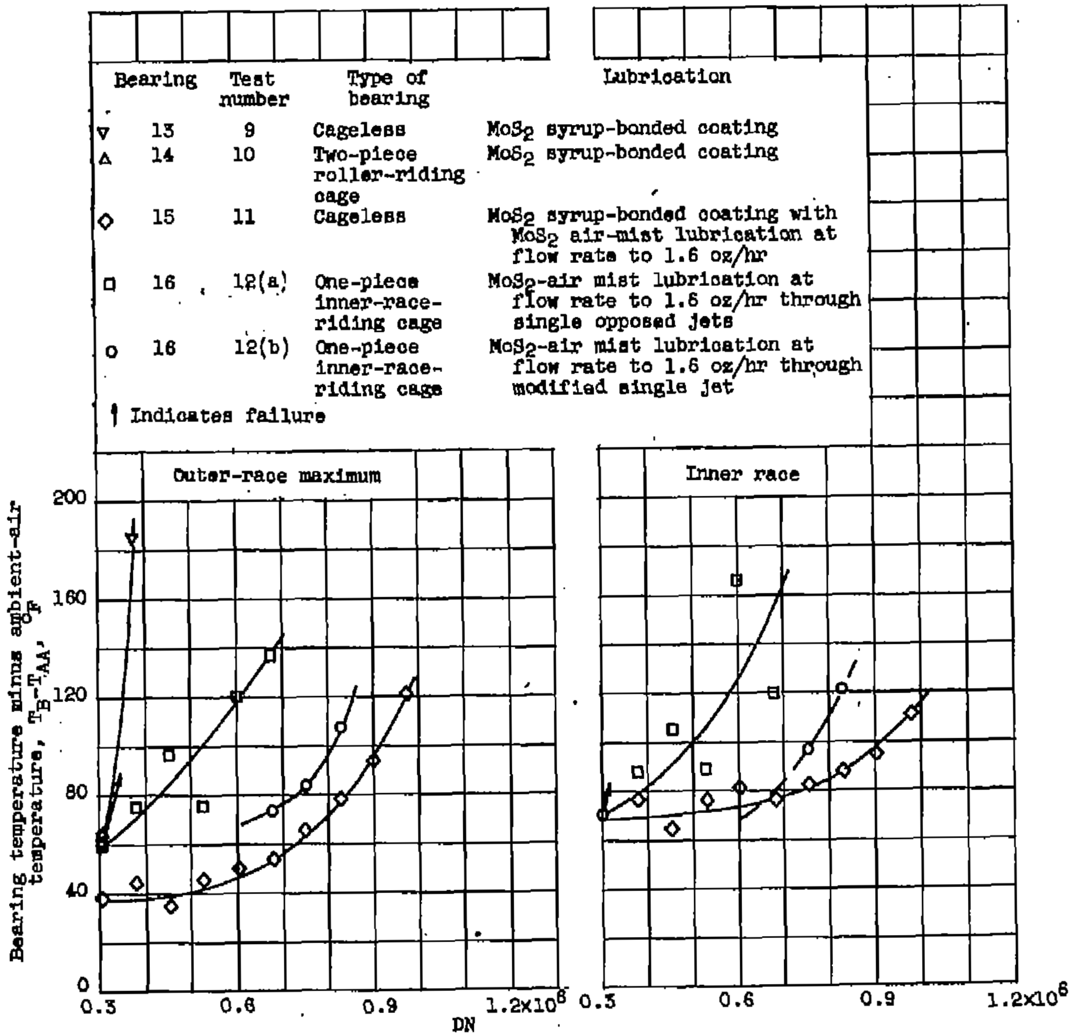


Figure 10. - Effect of DN on outer-race-maximum and inner-race temperatures above ambient-air temperatures for bearings 13, 14, 15, and 16 (with shaft seal). DN, 0.3×10^6 to 0.975×10^6; load, 368 pounds.

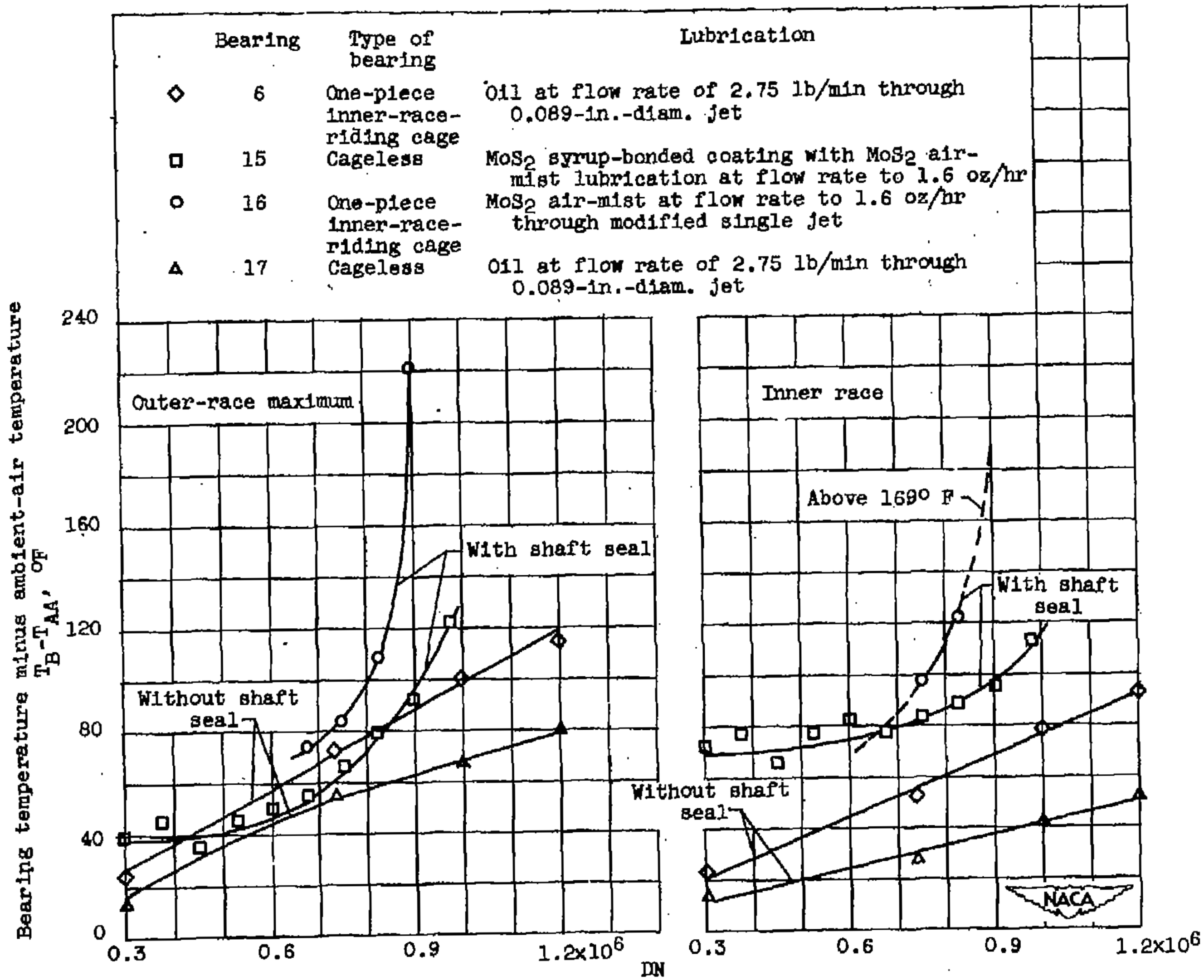


Figure 11. - Effect of DN on outer-race-maximum and inner-race temperatures above ambient-air temperatures for bearings 6, 15, 16, and 17. DN, 0.3×10^6 to 1.2×10^6; load, 368 pounds.