INVESTIGATION OF FRICTION, WEAR AND FAILURE IN AEROSPACE BEARINGS

H. E. STAPH
P. M. KU
SOUTHWEST RESEARCH INSTITUTE

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FOREWORD

The research effort described in this report was performed by Southwest Research Institute, San Antonio, Texas for the Mechanical Branch, Vehicle Equipment Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under USAF Contract AF 33(615)-1859. Mr. Paul C. Hanlon of the Air Force Flight Dynamics Laboratory was project engineer until January 1, 1965 when Mr. Phillip R. Eklund became project engineer. The research was conducted from July 1, 1964 to December 7, 1965 by H. E. Staph, P. M. Ku, and G. F. Munsch.

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This technical report has been reviewed and is approved.

FOR THE DIRECTOR

AIVARS V. PETERSONS
Actg Chief, Mechanical Branch
Vehicle Equipment Division
AF Flight Dynamics Laboratory

ABSTRACT

Operation of a facility for measuring cage and inner race temperatures of lightly-loaded 20-mm angular-contact ball bearings at high speed and vacuum is described. Results of tests on 440C ball bearings with MoS_2-epoxy compact cages at 300°F and with Niresist cages coated with MoS_2-graphite-sodium silicate solid film at 600°F are given. The latter bearings, for the short (about 1 hour) test time, ran smoother and with less raceway damage than did the bearings with the epoxy-MoS_2 cages.

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SECTION I

INTRODUCTION

The work described in this report was performed at Southwest Research Institute during the period from July 1, 1964 to December 7, 1965. It is a part of a long-range program investigating incipient failure in high-speed, high-temperature ball bearings such as would be used in aerospace rotating power equipment for flight vehicles.

The immediate effort has been in refining and defining the dynamic measurement techniques and in testing some specific bearing designs.

SECTION II

EXPERIMENTAL PROGRAM

Two sets of 204-size angular-contact ball bearings were examined. These sets were:

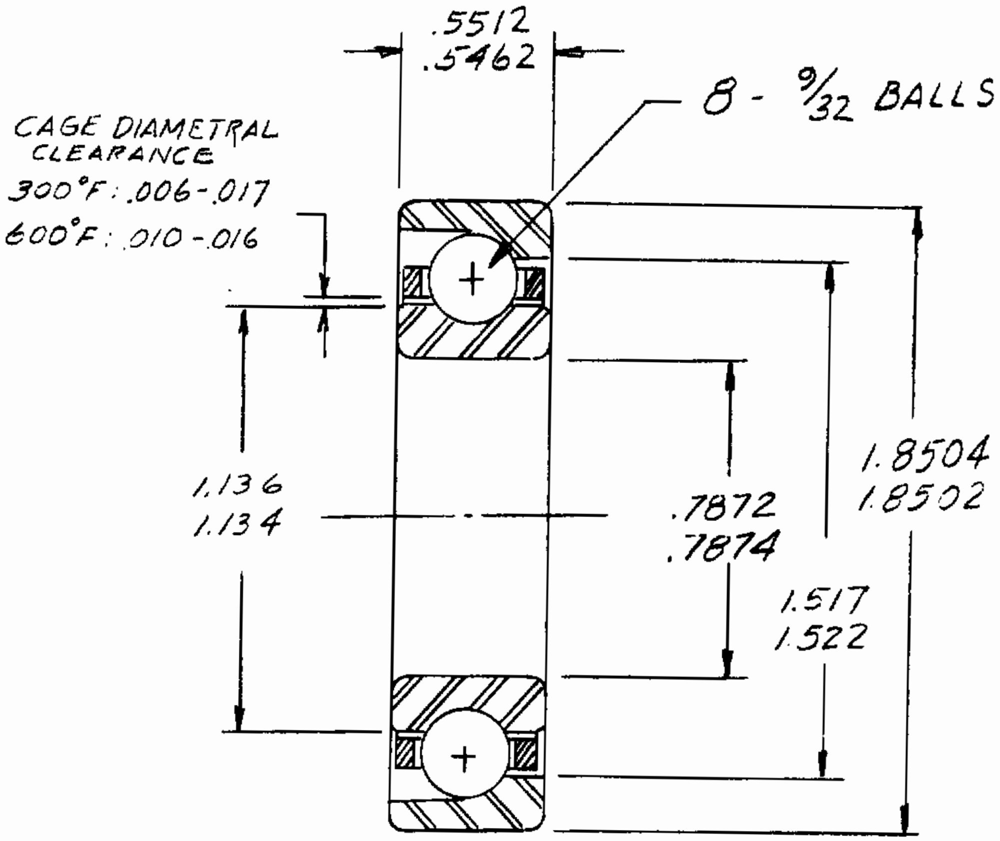
(1) 440C stainless steel balls and races, with Molykote M-1 MoS_2-epoxy compact cages;

(2) 440C stainless steel balls and races with Niresist cages coated with a MoS_2-graphite-sodium silicate solid film lubricant.(1)

Figure 1 illustrates the bearing used for both sets. Figure 2 shows the two cages, the MoS_2-epoxy compact being used for the 300°F tests and the coated Niresist cage used for the 600°F tests.

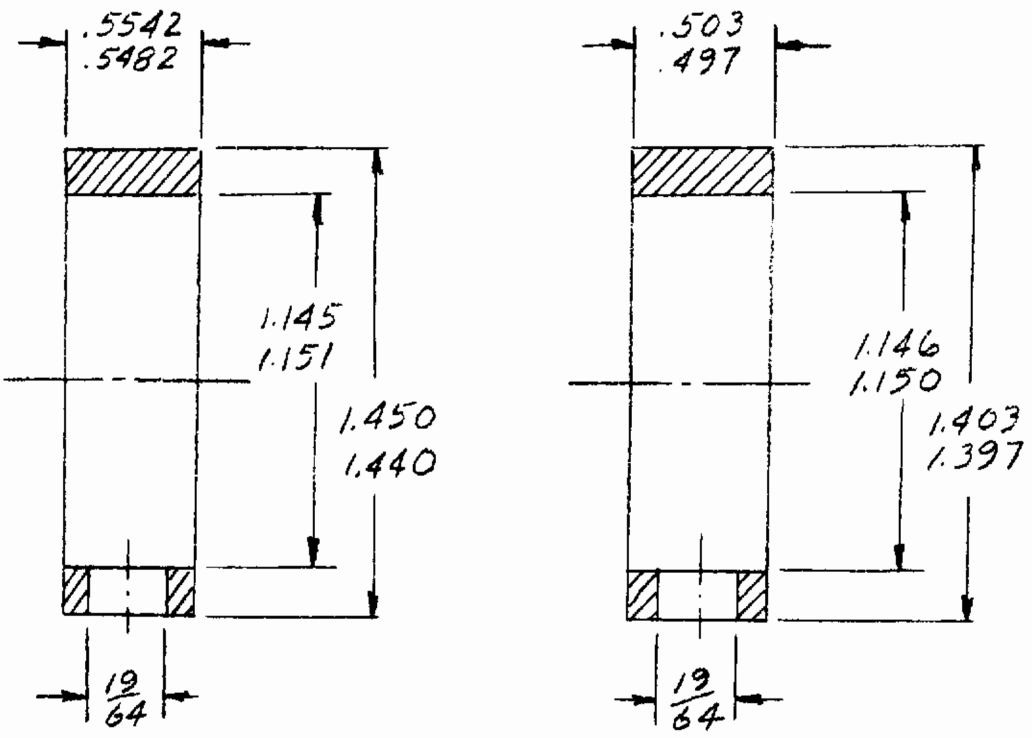
The nominal test conditions for Set 1 were 25-lb thrust load and 300°F outer race temperature. Test environment was to be air or nitrogen, and as high a vacuum as could be obtained. The bearings were to be run at 5000 rpm for 15 minutes, 10,000 rpm for 30 minutes, the highest speed that would generally assure cage temperature measurement capability for one hour, and finally 20,000 rpm for 15 minutes. Inner and outer race temperatures, friction torque, and cage temperature were to be measured.

Set 2 nominal test conditions were the same except for the outer race temperature level which was 600°F.



ABEC-5 Grade
Rings - 440C Stainless
Balls - 440C Stainless
All dimensions prior to treatment
Pitch dia. nominal 1.3256 in.
Race Curvature, nominal
    Inner 52%
    Outer 52%
Radial clearance prior to treatment:
    300°F: .0008-.0014 in.
    600°F: .0022-.0028 in.
Treatment:
    300°F: none
    600°F: coat races and O.D. of inner ring with MoS_2-graphite-sodium silicate

FIGURE 1. TEST BEARINGS



(a)

300°F operation
MoS_2-epoxy compact

(b)

600°F operation
Niresist, coated on all surfaces with MoS_2-graphite-sodium silicate solid film

FIGURE 2. TEST BEARING CAGES

SECTION III

TEST FACILITY

A detailed description of the test facility has been previously given(2). However, it is appropriate for completeness to repeat some of this earlier material.

The bearing test facility is a complex system formed by the integration of numerous subsystems. Essentially, the test bearing is located within a vacuum chamber with provisions for heating, loading, and driving it. The cage follower, described later in this report, is located alongside of the test bearing. It provides a "platform" from which the desired measurements are made on the operating test bearing. Electronic systems and vacuum systems complete the facility.

Figure 3 is a photograph of most of the complete facility. The test chamber is a 12-in. diameter by 14-in. long stainless steel cylinder. A 12-in diameter port is located on top of the chamber. This port provides access to the test region for adjusting and assembling purposes. While it is not shown in the figure, this large port also provides connection to a 650-in.^{2} titanium sublimation pump.

Behind the chamber may be seen the 400 ℓ/s ion pump, which, together with the above mentioned sublimation pump, is used to provide the chamber vacuum.

The port opposite the ion pump admits the induction heater coil. The heater leads are not shown in the photograph.

The left port contains the cage follower chamber, while the right port houses the test bearing drive chamber. The test bearing drive chamber is composed of a number of separately pumped regions surrounding the support shaft, and separated from each other by seals. One of these regions is evacuated by the 4-in. oil diffusion pump shown. This pump serves a dual purpose. Initial roughing of the chamber is accomplished by the fore pump attached to this diffusion pump. Then the diffusion pump is used to bring the chamber down to a pressure where the ion pump can be started. The tubulation for this pumping is the branch line shown in the photograph which contains the right-angle valve. After the ion pump is started, this valve is closed and the diffusion pump then serves solely to evacuate one of the aforementioned regions surrounding the test bearing support shaft.

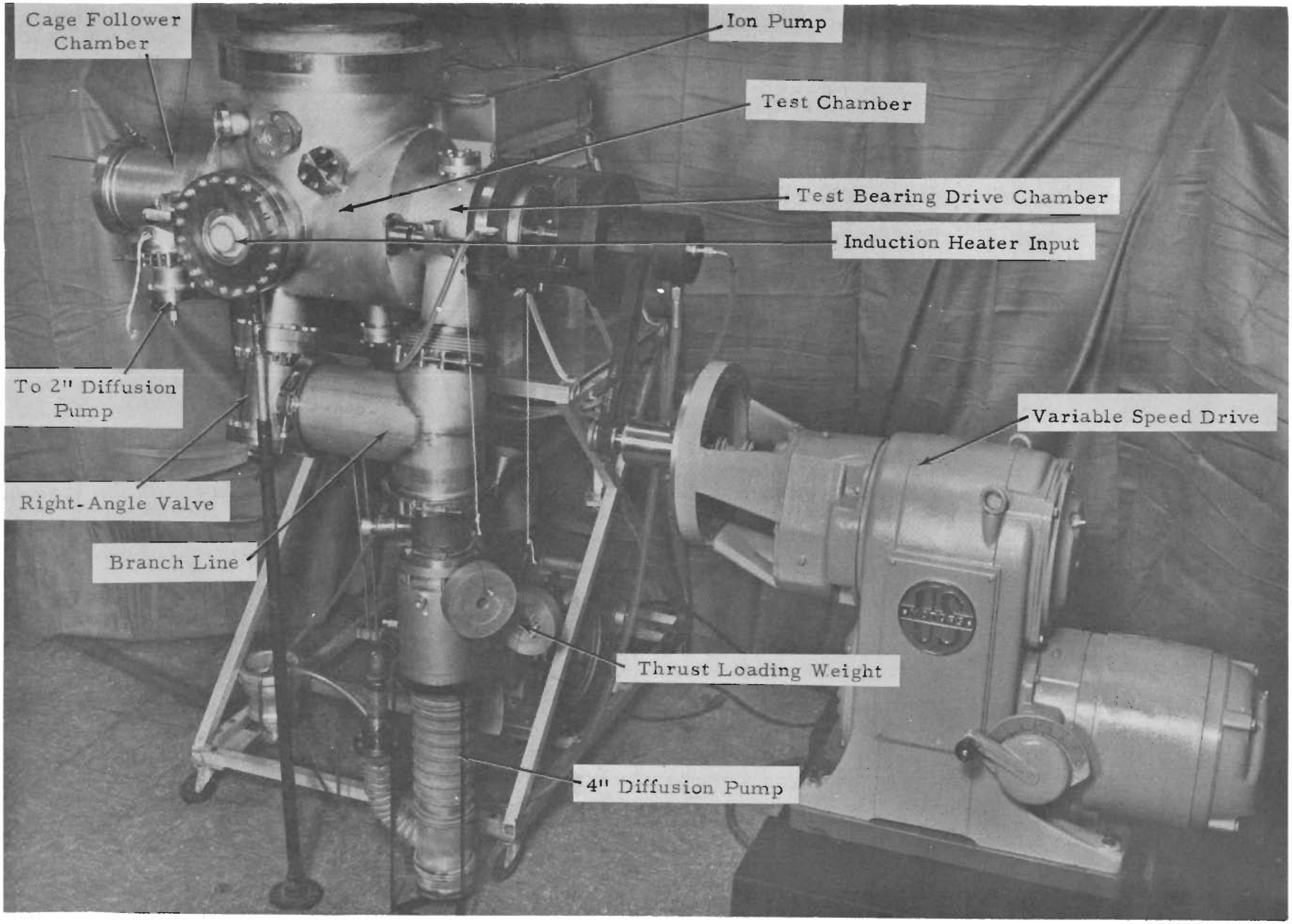


FIGURE 3. BEARING TEST FACILITY

A 2-in. oil diffusion pump, not shown in the photograph, evacuates the cage follower chamber. Two mechanical vacuum pumps, also not included in the photograph, evacuate regions in the test bearing drive chamber. The test bearing is driven by a 3-hp variable-speed drive having an output shaft speed of from 1000 to 10,000 rpm. A flat belt and pulleys raise these speeds to about 2000 to 20,000 rpm at the test bearing drive shaft. Short auxiliary or jack shafts are used at both the output shaft of the variable-speed drive and the test bearing drive shaft to take the radial load of the belt.

System pressure is measured with the ion pump and a cold cathode gage mounted on a flanged port on the chamber.

Figure 4 shows the cross section of the drive shaft chamber. The location of the seals separating the pumped regions may be noted. This method of differential pumping was necessary to achieve a large total drop in pressure with a high-speed shaft. Two thermocouples are shown embedded in the shaft and connected to the rotating transformer. In the actual facility, only one thermocouple was used. This thermocouple was used to measure inner race temperature.

Figure 5 shows the loading, heating, and torque-measuring methods. The bearing may be loaded radially to 30 lb by the removable heavy-metal ring and to any desired maximum load through the thrust load spider and external dead weight. For the work described in this report, a thrust load only of 25 lb was used.

Opposite the test bearing and located on the same axis as the drive shaft is the "cage follower" shaft. This shaft, completely separate from the drive shaft, is driven by a permanent magnet synchronous motor. Power is supplied by signals generated by photocells alternately switched on and off by a reflective portion of the cage side. The cage follower shaft motion is exactly synchronous with the cage motion at all speeds. Thus transducers may be mounted on the cage, their leads carried over to the follower shaft, and from there their signal may be telemetered to monitoring and recording instrumentation through rotating AC and DC transformers. In the present work, only DC signals from thermocouples were telemetered.

The DC signals are telemetered from both the rotating cage follower shaft and the test bearing drive shaft by passing a coil contained in the DC circuit, and which rotates with the shaft, past a stationary coil. The steady field established in the rotating coil cuts the stationary coil, setting up in it a counter EMF which is a function of the signal strength and the shaft speed. By previous calibration, the speed effect may be removed from the overall signal, leaving the signal due to the temperature effect only. Figure 6 shows signals representative of inner race and cage temperatures. The

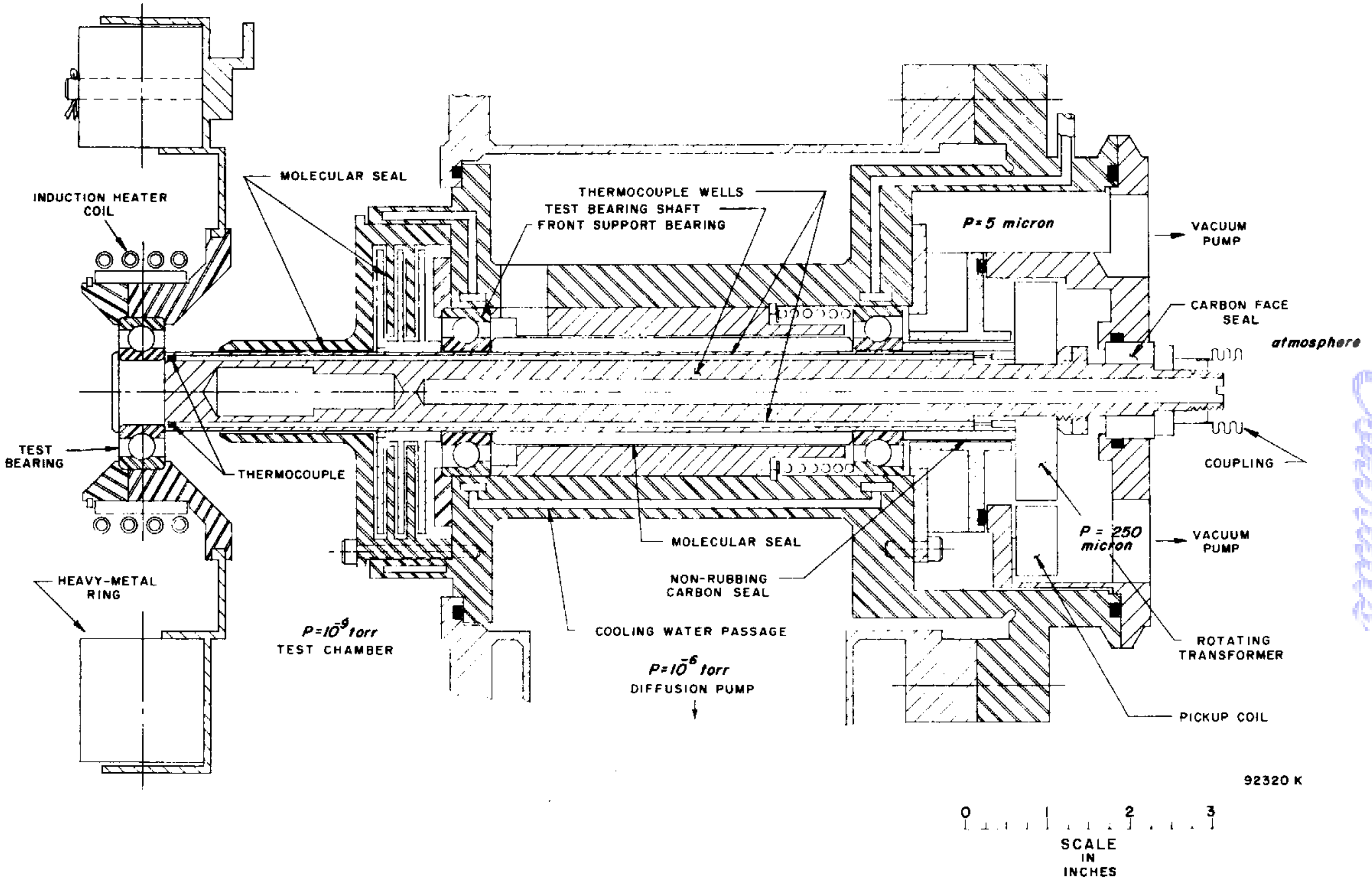


FIGURE 4. TEST BEARING DRIVE SYSTEM

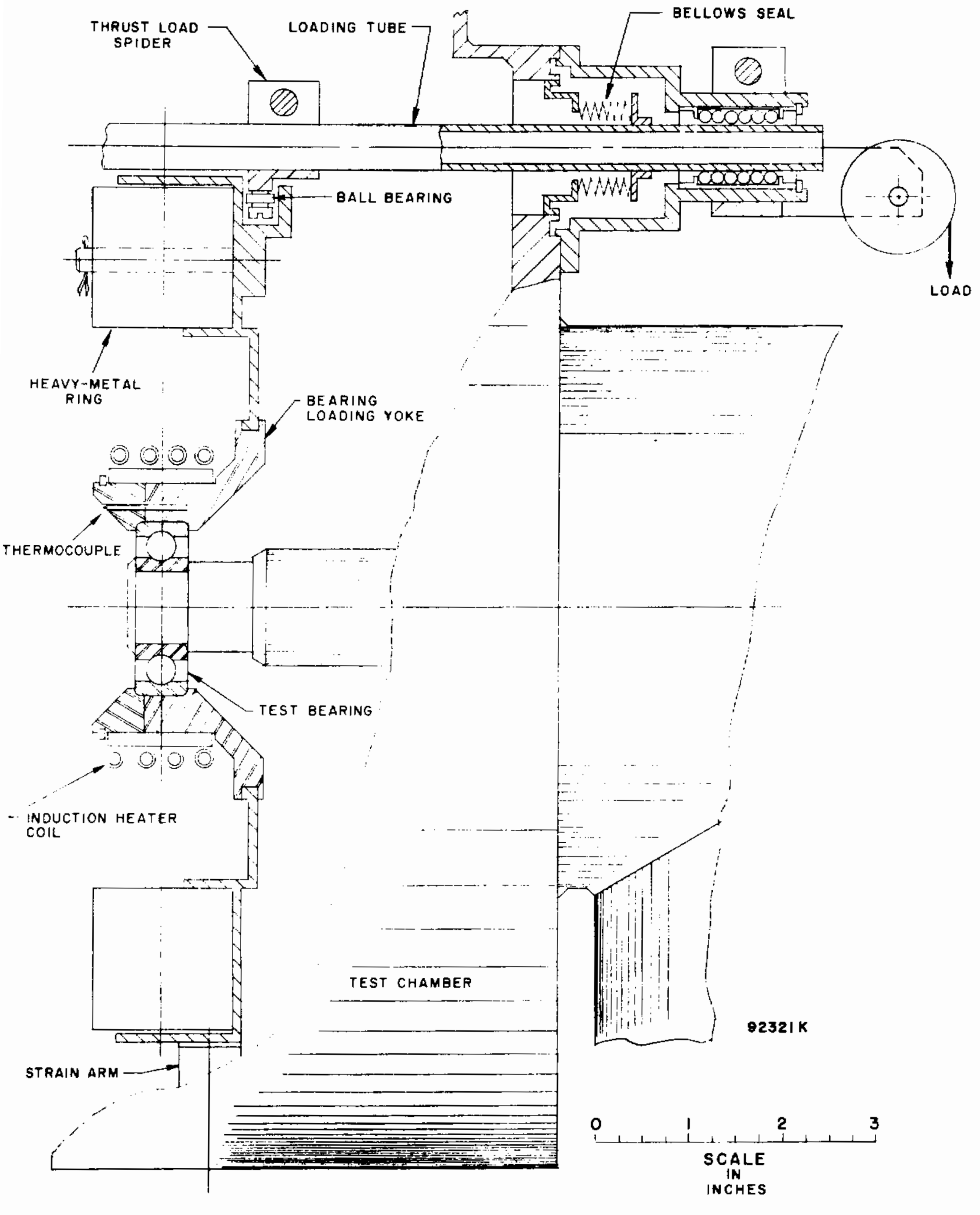


FIGURE 5. TEST BEARING LOADING, HEATING, AND TORQUE MEASUREMENT MECHANISMS

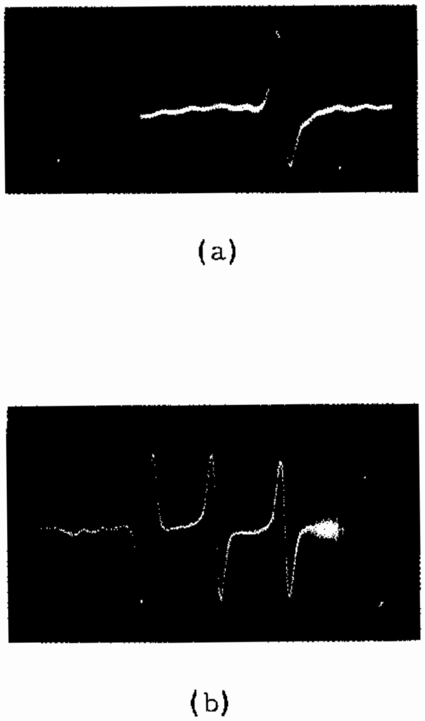


FIGURE 6. SIGNAL FROM TEMPERATURE TELEMETERING COILS
(a) Shaft temperature, 493°F at 5000 rpm, 0.2 mv/cm gain
(b) Cage temperature, 553°F at 1000 rpm, 0.1 mv/cm gain

trace of the cage temperatures shows three peaks. Each peak represents the temperature of a separate thermocouple located in the cage. In order to achieve a "clean" signal it is very important that the stationary coil be well shielded magnetically, and that absolutely no magnetic fields rotate near the stationary coil without considerable magnetic shielding between. Figure 7 shows the cage follower drive shaft with the telemetering transformers and drive motor. The chamber containing the cage follower drive shaft is separated from the test chamber by the molecular seal through which the shaft passes. This cage follower chamber is pumped by a small oil diffusion pump.

Figure 8 illustrates the optics bank. Each of the completely adjustable blocks contains a lamp and a sensitive light sensor or photocell. Through a system of mirrors and lenses, the light is directed from the lamp to the reflecting portion of the cage side and thence back to the light sensor. With 180° of the cage side reflecting and 180° nonreflecting and the optics blocks spaced 120° apart, light sensors are being switched on or off every 60°, resulting in a rotating 3-phase output signal to the motor.

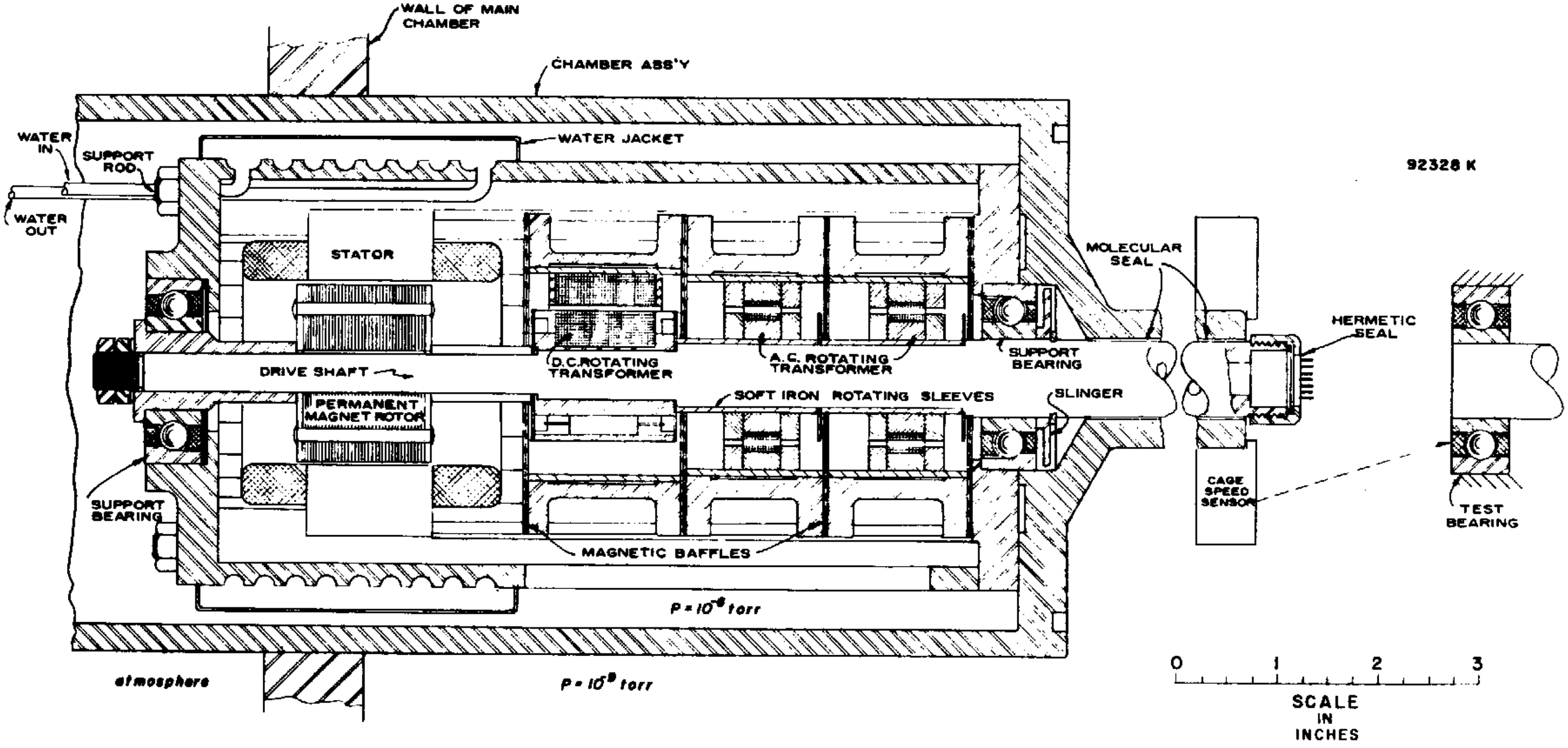


FIGURE 7. CAGE FOLLOWER DRIVE SHAFT WITH TELEMETERING COILS AND MOTOR

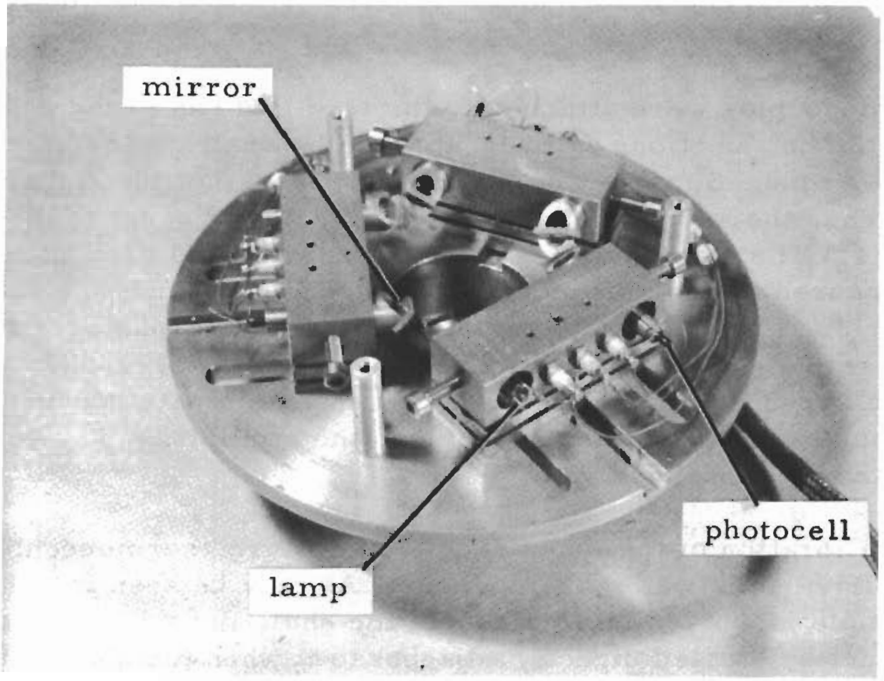


FIGURE 8. OPTICS BANK

SECTION IV

CALIBRATION

The cage follower and drive shaft thermocouples must be calibrated under dynamic conditions since the signal coupling between the rotating and stationary coils depends on the stationary coil cutting the constant field force lines of the rotating coil which is part of the D. C. thermocouple circuit.

Thermocouples were attached to the terminal end of the cage follower shaft so that the hot junctions were located on the shaft centerline. A clamshell heater was placed in position to surround these hot junctions. A stationary reference thermocouple was placed directly adjacent to the other thermocouples. The clamshell heater was turned on and brought to an equilibrium as measured on the reference couple. The cage follower shaft was rotated at various speeds and the resulting signals were photographed on the oscilloscope screen. Thus signal deflections versus corresponding temperature at various speeds were plotted. In order to eliminate convection heat transfer around the rotating thermocouples, the calibration was conducted in a vacuum in the neighborhood of 10^{-5} torr.

The calibration of the inner race temperature thermocouple on the test bearing drive shaft was more difficult. As may be seen in Figure 4, the thermocouple is welded into the end of the shaft and a reference thermocouple could not be located directly adjacent to it when the shaft turns.

The bearing inner race mounts on a TiC cermet sleeve which is in turn fastened to the shaft by a draw bolt. For temperature calibration, a cermet sleeve was fastened to the shaft without the bearing race. A clamshell heater surrounded the sleeve. The sleeve was heated to a temperature near that desired and then the shaft was rotated at a specific speed for a few minutes while the signal was adjusted on the oscilloscope screen. The shaft was stopped, the heater pushed slightly to expose a portion of the sleeve, and the temperature of the sleeve was measured with a contact type probe. The heater was pushed back in place and the shaft rotated. The signal on the oscilloscope screen was photographed. The magnitude of the signal was visually observed to see that it had not changed from this magnitude during the previous or initial period of rotation. Then the shaft was stopped and the temperature of the sleeve was again measured by the contact probe. The initial and final readings had differences of up to about 12°F. The average was used for calibration.

Ordinarily, the use of contact probes to measure surface temperature is grossly inaccurate. However, following the general procedure developed by the Cornell Aeronautical Laboratory (3), a special probe was built that overcame the problem of inaccuracy. This probe consisted of a sandwich of the surface-contacting thermocouple, a thin layer of electric insulation, a reference thermocouple, another thin layer of electric insulation, and a heater. If the heater output were adjusted to make the reference thermocouple read the same as the contact thermocouple, there would be no net heat transferred across them, and the temperature measured by the surface thermocouple would be the real surface temperature. The system described in the referenced report used automatic means for adjusting the heater output to stabilize the temperatures of the two thermocouples. In the present case, the adjustment was performed manually and required considerable trial and error to achieve satisfactory results.

As mentioned earlier, the signal observed on the oscilloscope was a function of both voltage across the rotating coil and shaft speed. Above 10,000 rpm, this dependence on speed was no longer observable with the pickup coil used and the stationary pickup coil became saturated, responding only to changes in the rotating coil voltage due to temperature changes.

SECTION V

TEST RESULTS

This section will include a description of each test, giving a temperature-torque-speed versus time profile, and some bearing parameters.

Since the bearing test program and the facility capability evaluations were conducted simultaneously, at least during the early part of the program, the tests exhibit some variations in operating parameters. Hence, more emphasis is placed on the behavior of the bearing and facility together, with less emphasis on the repeatability of data for a class of bearings.

All bearings were of 440 C stainless steel races and balls. Those bearings tested at 300° F had MoS_2-epoxy cages and those tested at 600° F had Niresist cages coated with an MoS_2-graphite-sodium silicate solid film. The cages were, in both bearings, inner race controlled. A thrust load of 25 lb was used in all tests.

In order to provide a reflective surface on the side of the cage, the MoS_2-epoxy cages were banded with narrow rings of stainless steel. The rings, one on each side of the cage, were attached with small screws passing through holes drilled in the cage. The stainless steel ring facing the cage follower optics bank was polished on a metallurgical wheel. Then one-half of this surface was sandblasted to provide the required nonreflecting surfaces.

Since the Niresist cages, being metallic, could be polished, it was unnecessary to provide the stainless steel cladding.

The bearing test numbers consist of two parts--a prefix indicating the nominal test temperature, either 300° F or 600° F, and a chronological test number.

The recorded contact angle was determined by noting the number of turns of the cage for 10 turns of the inner race, while under a thrust load of 25 lb, and using Equation 50 of Reference 4. The contact angle was measured prior to testing. In the case of the 600° F test bearings, the cage and race coating reduced the radial clearance to the point where the bearing did not turn very freely. However, after a few minutes of operation the coating was smoothed, the bearing turned freely, and the contact angle changed. After testing, the contact angle under 25-lb thrust load was again determined, this representing the condition after the coating had been smoothed out and/or worn off.

The cage radial clearance is the radial clearance between the cage inner surface and its piloting surface on the inner race.

Percent cage weight change is based on the bare weight of the cage as received, which excludes the weight of the stainless steel reflecting rings used for the 300°F bearing cages.

Accompanying each test description is a graphic plot of the changes in the recorded data. The cage follower temperature is the average of two thermocouples, whenever two were functioning. The absence of an environment pressure trace means that the test was conducted in either an air or nitrogen environment at atmospheric pressure.

The speed shown is the inner race speed. Generally speaking the cage speed was about 40 percent of the inner race speed.

The results of tests 300-1 through 600-12 follow.

Test 300-1

Nominal test temperature: 300° F

Bearing: 204 R-ST-46, Serial 1A, dated 1/65

Cage: MoS_2-epoxy compact, machined

Contact angle: 25 lb load, before test, 18.6°

Cage radial clearance: Not measured

Cage weight change: Not measured

Final description of bearing:

Inner surface of cage showed considerable rubbing at two diametrically opposed regions, indicating out-of-roundness of cage. A ring worn into outer surface where cage contacted outer race land. Heavy ball pocket wear. Inner raceway lightly etched. Balls very lightly pitted. Balls had light burnished coating of MoS_2. Outer race had narrow etched path. Distinct evidence of ball having run on shoulder relief.

Test description:

This was the first bearing tested. It was started in a vacuum of about 4×10^{-6} torr which quickly rose to 1×10^{-5} torr. Since this was the first test, it was decided not to run for very long at any one speed. The bearing outer race temperature was stabilized at 300° F and upon starting the test, the heater was shut off. The bearing was run up over a period of ten minutes from 1000 rpm to 10,100 rpm whereupon the cage follower lost synchronization and the cage thermocouples broke. The pressure rose to 3×10^{-5} torr. It was decided to continue the test, in a nitrogen atmosphere.

From Figure 9, it may be seen that the bearing outer race cooled from its initial 300° F until the outer and inner race temperatures were virtually equal. Friction heating eventually increased both temperatures, the inner race finally exceeding that of the outer by 125° F. The rig design is such that in an air or nitrogen environment, the outer race may lose heat more readily than the inner. This may account for the higher final temperature of the inner race.

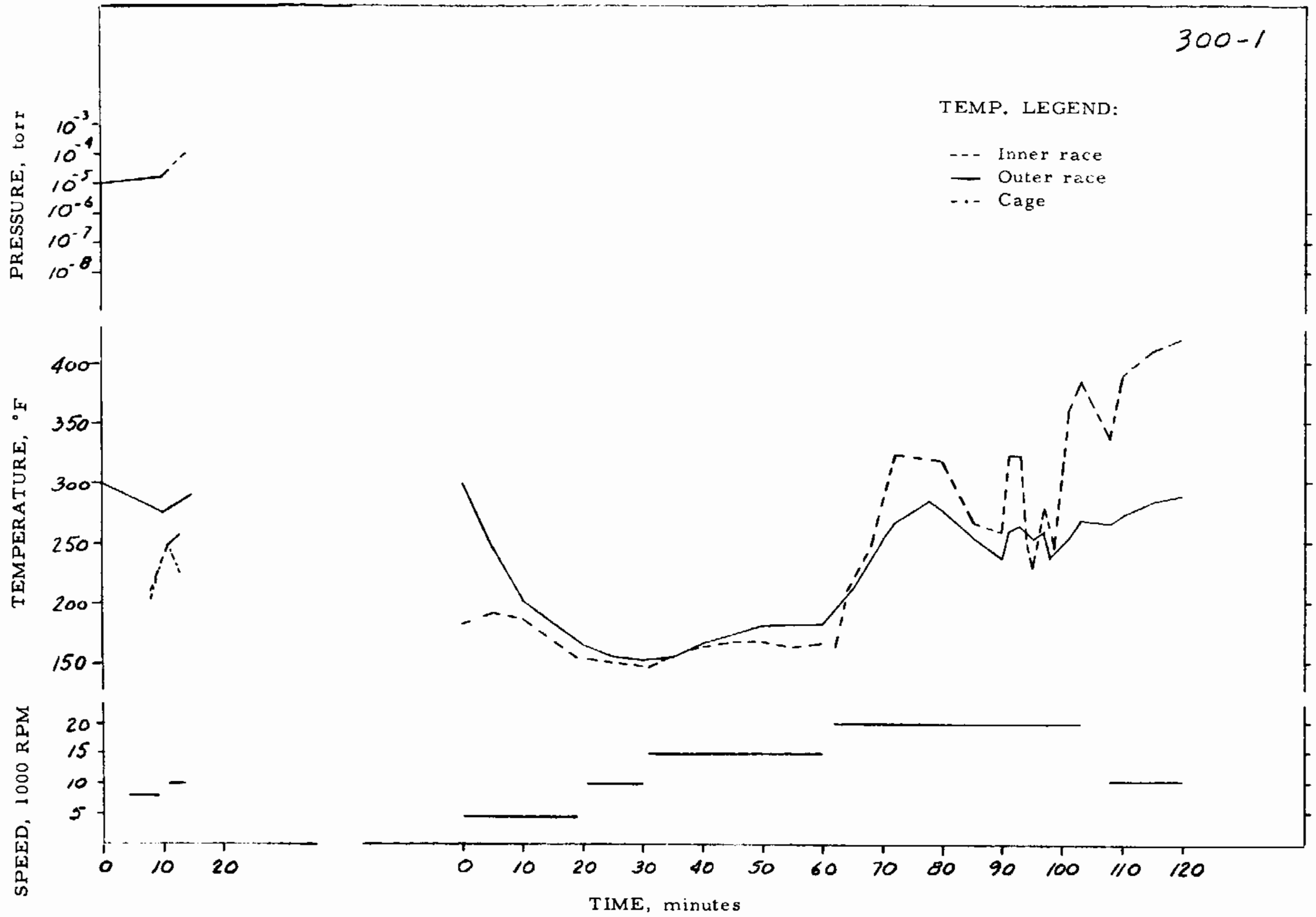


FIGURE 9. PERFORMANCE CURVES FOR TEST 300-1

The cyclic nature of the temperatures is probably due to a loss of radial clearance which, with an accompanying friction increase, heated the outer race sufficiently to then increase clearance. Torque fluctuation with temperature was noted qualitatively but not recorded due to malfunction of the torque-measuring system.

Test 300-2

Nominal test temperature: 300° F

Bearing: 204 R-ST-46, Serial 2A, dated 1/65

Cage: MoS_2-epoxy compact, machined

Contact angle: 25 lb thrust, before test, 7.7°

Cage radial clearance: 0.0074 in.

Cage weight change: 1.16% loss

Final description of bearing:

Slight, uniform rubbing on inner surface of cage. No sign of contact on outer surface. Light, but significant ball pocket wear. Inner raceway lightly etched. Balls clean and lightly pitted. Outer race smooth.

Test description:

This test was conducted in an air environment at atmospheric pressure. Torque was not recorded due to equipment malfunction. Outer race temperature was maintained constant at 300° F. The cage follower lost synchronization and stopped, destroying the cage thermocouples, just after the shaft speed was increased to 17,800 rpm.

The test was terminated because the temperature of the front support bearing on the drive shaft began to increase uncontrollably.

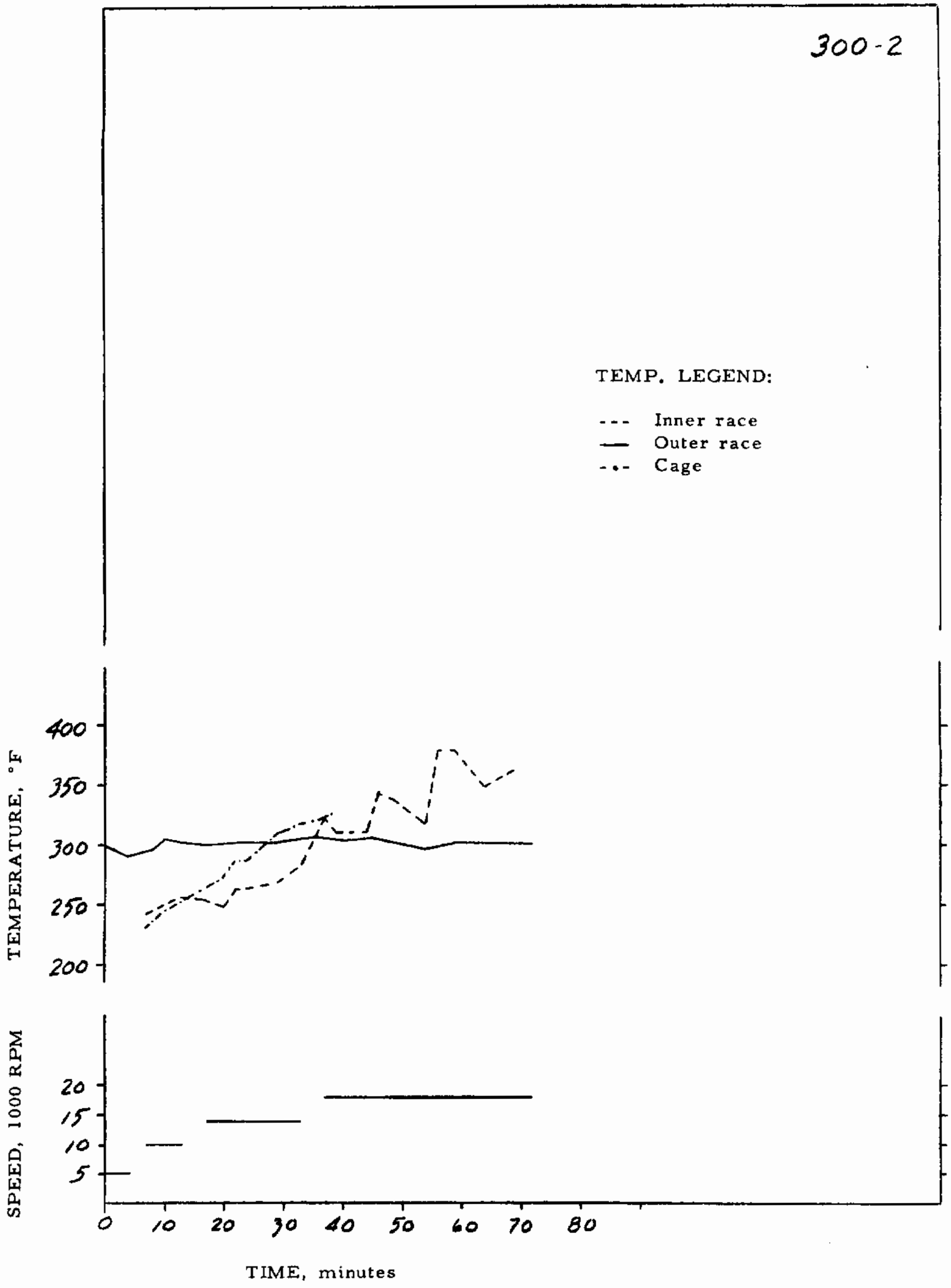


FIGURE 10. PERFORMANCE CURVES FOR TEST 300-2

Test 300-3

Nominal test temperature: 300° F

Bearing: 204 R-ST-46, Serial 3A, dated 1/65

Cage: MoS_2-epoxy compact, machined

Contact angle: 25 lb thrust, before test, 9.6°

Cage radial clearance: 0.0067 in.

Cage weight change: 1.60% loss

Final description of bearing:

Light, spotty wear on inner surface of cage. No contact on outer surface. Light wear in ball pockets. Inner raceway lightly etched. Some evidence on inner race of poor alignment. Outer race had narrow etched path. Balls had heavy burnished coating of MoS_2. Very lightly pitted.

Test description:

This test was made in a vacuum environment starting at 5×10^{-6} torr. A faulty start broke the cage thermocouples at the beginning of the test so no cage temperatures were measured. Continuing torque-measuring problems resulted in only qualitative evaluation of torque. It appeared to be high.

When the speed was increased from 10, 000 rpm to 15, 000 rpm, the test bearing vibrated badly and a large amount of gas was given off of the cage. The vacuum environment was lost and the torque increased many-fold. The test was immediately terminated.

The inner race of the test bearing showed distinct signs of having been misaligned, which would account for the large evolution of gas and the high torque. Subsequent checking revealed some misalignment of the load ring with respect to the drive shaft. This was corrected, but later results demonstrated that even more rigid alignment checks were necessary.

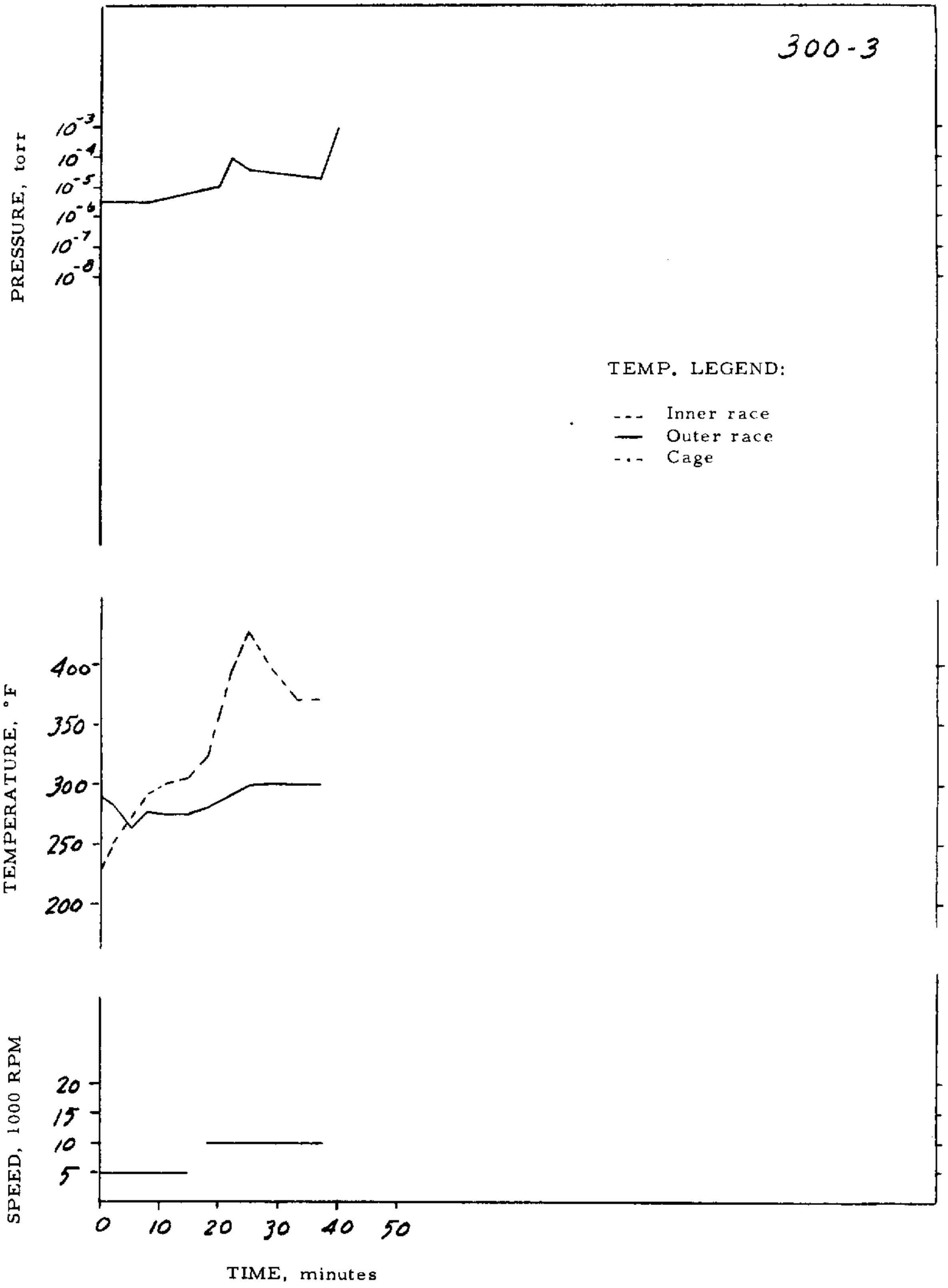


FIGURE 11. PERFORMANCE CURVES FOR TEST 300-3

Test 300-4

Nominal test temperature: 300° F

Bearing: 204 R-ST-46, Serial 10A, dated 1/65

Cage: MoS_2-epoxy compact, machined

Contact angle: 25 lb thrust, before test, 9.3°

Cage radial clearance: 0.0071 in.

Cage weight change: Not measured

Final description of bearing:

Cage slightly rubbed on inner surface. No contact on outer. Ball pocket wear moderate. Inner race ball path moderately frosted showing Heathcote bands. Balls are pitted with faint suggestion of a ring. They are clean and not coated with MoS_2.

Test description:

This was a nitrogen atmosphere test. When the speed was increased to 10,000 rpm, the cage follower dropped out of synchronization and shortly afterward the test bearing tied up and stalled. Several restarts resulted in stalls. The following day new cage thermocouples were installed and the system was run again in air, without a very long presoak at temperature. The system performed nicely up to 15,000 rpm. When the speed was increased to 18,000 rpm the cage follower dropped out and the test was terminated.

The torque-measuring system failed after a few minutes when one of the ceramic bonded strain gages on the torque sensing arm became unbonded.

It is of interest to note that in the first test of this bearing, the system had soaked at 300° F outer race temperature for several hours. The long soak resulted in a cage temperature approximately equal to the outer race temperature, and greater than that of the inner race. The second run had a brief soak and the cage did not have time to reach a high temperature. On the other hand, the inner race temperature was nearly as high as in the previous start.

After the bearing had run for a short period, it appears that windage had a pronounced effect on cage temperature and it in turn kept the inner race temperature depressed. Toward the end of the second run, the normal flow of heat from the outer to the inner race, together with friction, had begun to raise these temperatures.

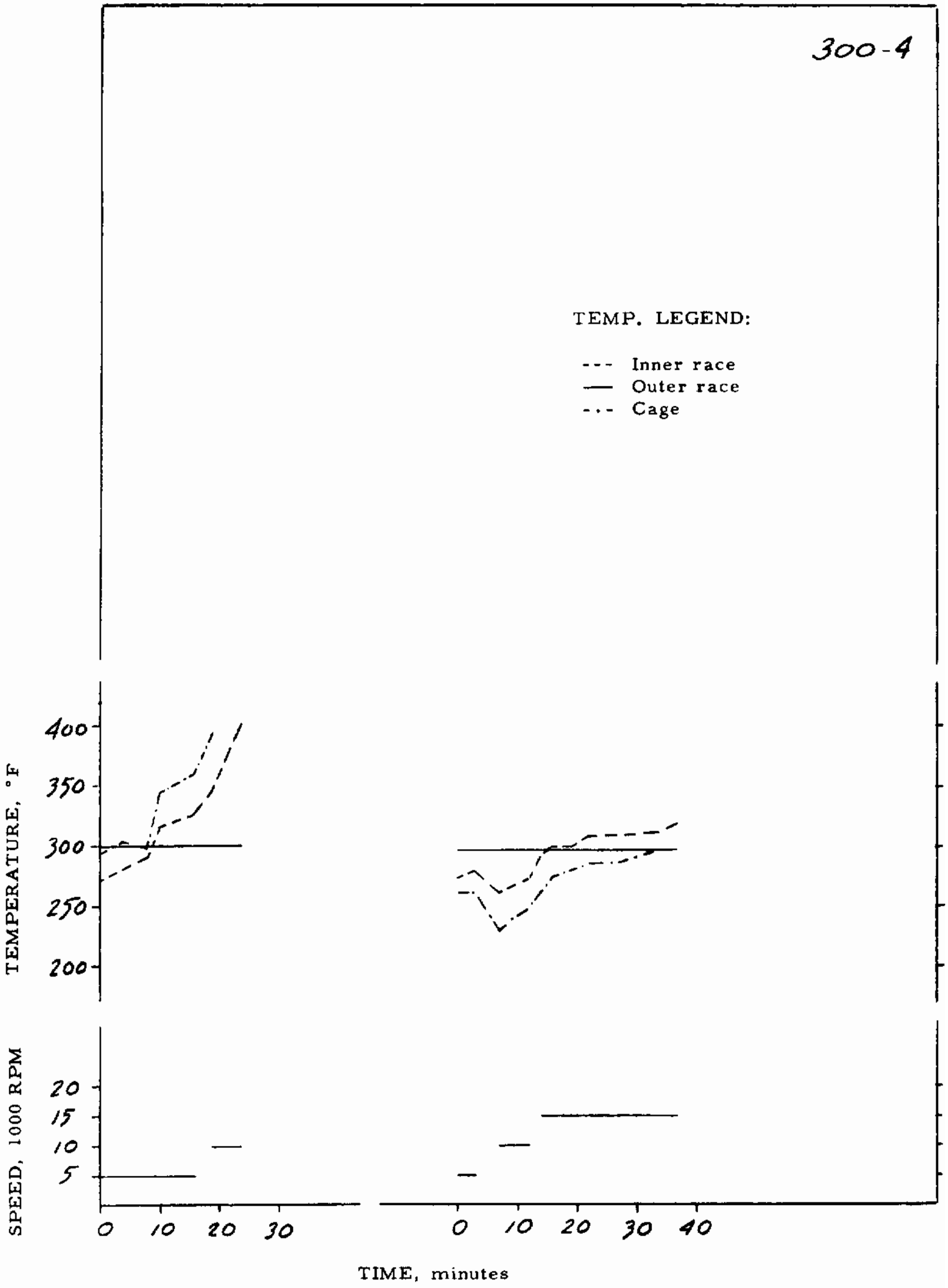


FIGURE 12. PERFORMANCE CURVES FOR TEST 300-4

Test 300-5

Nominal test temperature: 300° F

Bearing: 204 R-ST-46, Serial 9A, dated 1/65

Cage: MoS_2-epoxy compact, machined

Contact angle: 25 lb thrust, before test, 18.4°

Cage radial clearance: 0.0082 in.

Cage weight change: Cage destroyed during test

Final description of bearing:

Cage broken up by pieces flinging off of outer surface. Pieces held together only by stainless steel cladding rings. Severe rubbing on inner and outer surfaces. Ball pockets show some distortion. Inner race and lands burnished with MoS_2. Ball path not etched but shows signs of gross layering of MoS_2. Layering appears also on outer raceways. Balls heavily burnished with MoS_2. Very slightly pitted.

Test description:

This was a test in air. The bearing ran noisy from the beginning and a strong smell of hot epoxy became evident very early. The temperature curve for the cage shows a peak at about 7 minutes of slightly over 400° F. This temperature is sufficient to scorch many epoxies.

When the speed was increased to 10, 000 rpm, the noise abated somewhat. One cage thermocouple was lost. After approximately 35 minutes of operation at a speed of 10, 000 rpm, the remaining cage thermocouple signal became intermittent. Later, this was traced to the small pin-and-jack used to attach the thermocouples to the hermetically sealed header in the end of the cage follower shaft. Vibration and centrifugal force tended to spring the pin-and-jack in such a way as to momentarily break contact.

At 15, 000 rpm, the bearing would occasionally emit a high pitched squeal - more in the range of a high musical note. At these points the torque would momentarily drop to a low value.

When the speed was increased to 20, 000 rpm, the friction became so great as to raise the outer race temperature above the 300° F controlled value at a rapid rate. At 120 minutes of testing, the bearing gave out a cloud of smoke and failed completely.

The torque-measuring system operated successfully for this run. The plot shown on Figure 13 indicates average values. Actually, during most of the operation at 5000 rpm, except for one peak, the bearing load ring vibrated at high frequency so that the torque trace was extremely noisy. This noise appeared more likely related to the overall vibration level of the system and its resonant frequencies than to actual torque variation. However, above 10, 000 rpm there were varying periods of several minutes when the frequency and magnitude of the "noise" was more indicative of real sticking in the smooth operation of the bearing. Ratios between the high and low torques were then as high as 3 to 1, with periods of from 1 to 3 or 4 seconds. Since this period was very much greater than the period of rotation of the bearing, the torque variation may have been due to erratic cage and ball behavior. Certainly, the final condition of the cage lends emphasis to abnormal cage operation. Figure 14 shows these types of torque recordings which are typical of other runs.

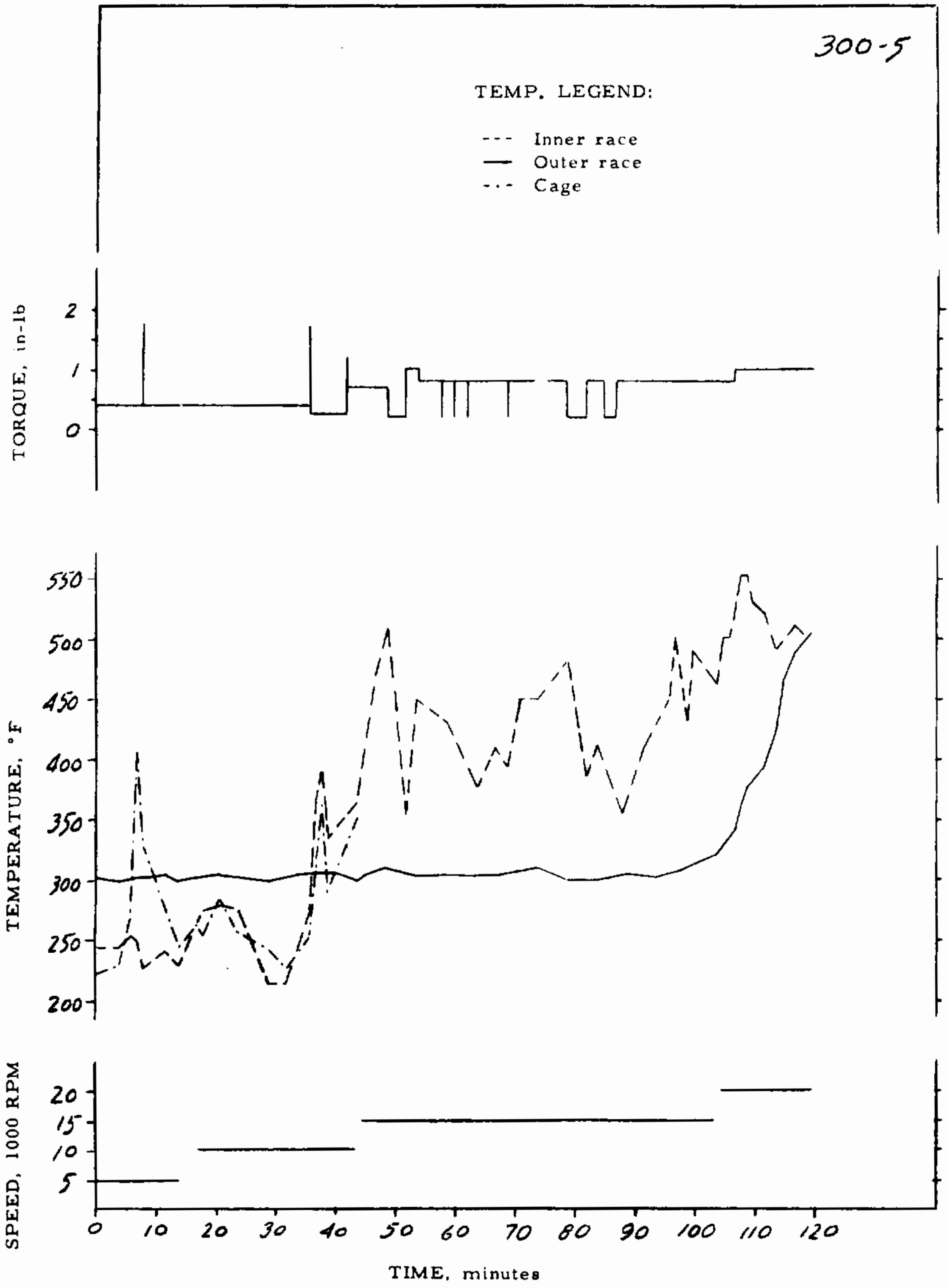
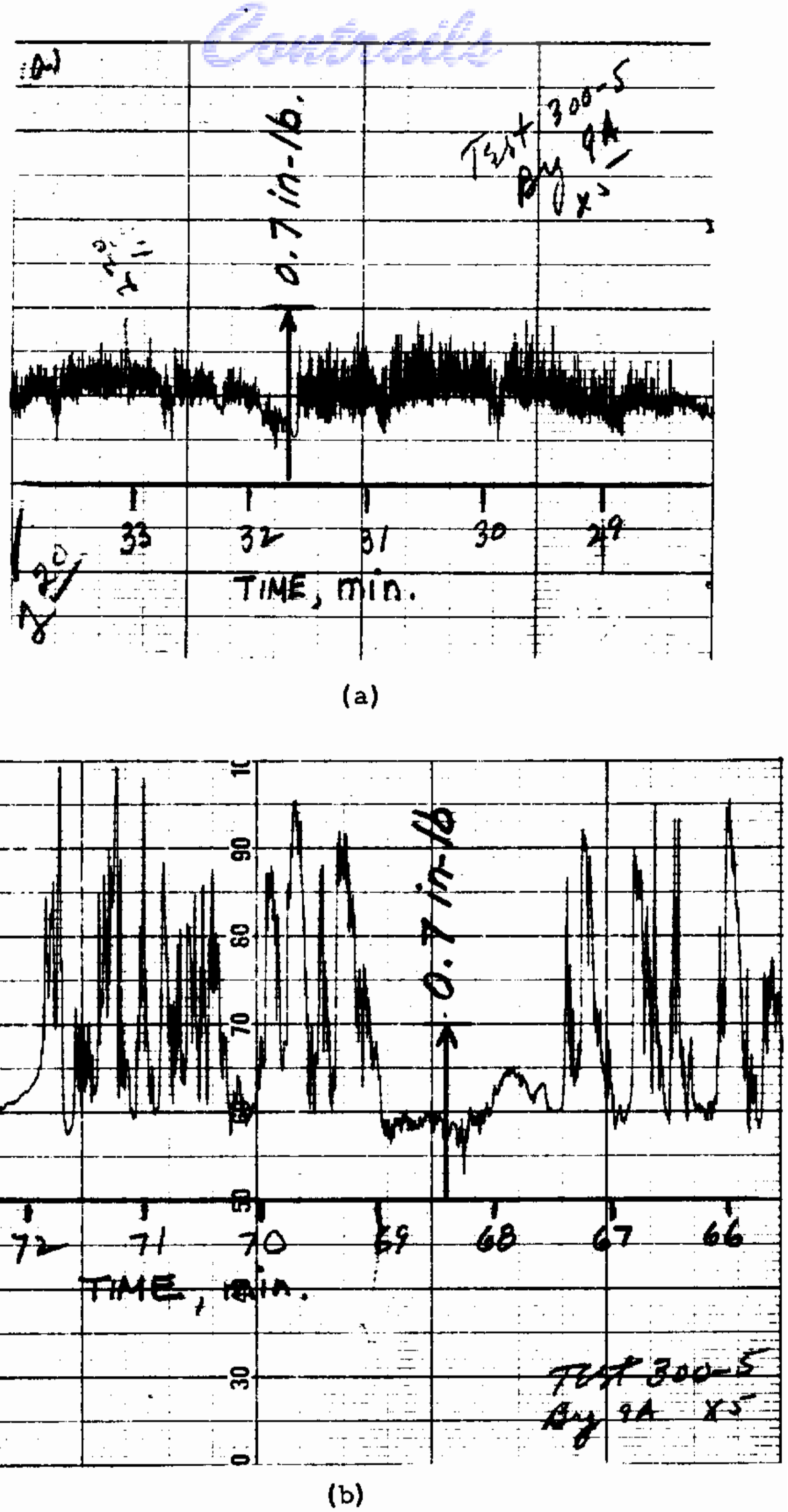


FIGURE 13. PERFORMANCE CURVES FOR TEST 300-5



(a)

(b)

FIGURE 14. TYPICAL TORQUE TRACES
(a) high frequency vibration
(b) intermittent sticking

Test 300-6

Nominal test temperature: 300° F

Bearing: 204 R-ST-46, Serial 5A, dated 1/65

Cage: MoS_2-epoxy compact, machined

Contact angle: 25 lb thrust, before test, 18.4°

Cage radial clearance: 0.0069 in.

Cage weight change: Not measured

Final description of bearing:

Cage uniformly rubbed on inner surface. Not touched on outer surface. Ball pockets moderately worn. Pieces broken out of outer surface. Inner raceway shows moderate etching in two distinct bands. Outer race lightly etched. Ball pitted, clean.

Test description:

This test actually comprises 4 short tests over a period of 5 days. The first three tests were in vacuum environment; the last in nitrogen.

The first test was stopped when the drive shaft speed began to fluctuate. It was possible that either the test bearing or one of the drive shaft support bearings was seizing. Since examination of the test bearing did not reveal an obvious problem, the drive system was dismantled and the rear support bearing retainer which was badly worn was replaced.

Torque during the 5000-rpm phase of the run had been reasonably constant with the same high frequency vibration of the outer race support and load ring. However, the amplitude of the vibration was about 1/3 to 1/4 of that previously reported. For the first time, a suspected phenomenon was vividly seen via the torque traces. Whenever the induction heater went on, the torque dropped almost immediately to about 20 percent of its normal value, and remained so for the approximately 5 seconds that the heater was on. When the heater stopped, the torque gradually rose again to its former value, only to repeat the cycle when the heater came on again. The induction heater, due to its characteristic of heating directly only the outer portion of the bearing outer race holder, would cause the holder to quickly expand. This reduced the bearing preload and hence the torque. When the heater shut off, the outer race was once again tightened up on the balls, increasing torque.

Torque during the latter part of the 10,000 rpm phase became very erratic with wide fluctuations.

The second run several days later was stopped after about 45 minutes because the outer race temperature began to rise uncontrollably. The torque was far more uniform than during the first run but was still more variable than was believed normal. No logical reason was found for the rise in inner race temperature.

Two days later a third run was attempted. The shaft began to stall shortly after going to 10,000 rpm. Repeated starts were to no avail. The cage follower did not lose synchronization during either the second or third runs.

Following the unsuccessful attempts to restart the last run, the system was let up to nitrogen and a fourth run started. It will be noted in Figure 15 that the cage temperature dropped considerably when the gaseous environment allowed heat to be carried off by convection. This run operated satisfactorily until the cage follower dropped out upon going to 15,000 rpm. The test was terminated. The torque during this last run was quite uniform.

There still persisted the feeling that it was the drive shaft support bearings and not the test bearing that were causing the stalling conditions encountered during this run. It will be noted that this test, No. 6, was a vacuum run (except for the fourth attempt). Only two other vacuum runs had been tried, a brief portion of Test 300-1 and Test 300-3. The experience in Test 300-1 was too brief to evaluate. In Test 300-3, however, the drive vibrated when attempting to go above 10,000 rpm and the torque-measuring system went off-scale. The system was of course stopped. In Test 300-6, the test bearing did not obviously fail, and thus it was possible that potential shortcomings of the drive system in vacuum were manifesting themselves. In a vacuum test, the majority of the heat in the test bearing must leave through the drive shaft, and thus heats the front support bearing. In air or nitrogen, the bearing loses heat to the surrounding gaseous environment, and not as much escapes down the drive shaft. Hence, in the latter case, the front support bearing retains some running clearance but in the former case it begins to seize.

The drive shaft was dismantled and both bearings carefully examined. The rear bearing, which had just had its cage replaced, appeared in excellent shape. The front support bearing retainer was badly worn, with distorted ball pockets and large ridges where the cage rode on the inner race lands and touched the outer race lands.

The front support bearing was a 205 angular-contact ball bearing with 9 balls of 0.3124-in. diameter. The balls were replaced by 0.3116-in. diameter aluminum oxide balls. An MoS_2-epoxy compact cage was used, with rather large radial clearance between the cage inner surface and the inner race lands. That this change was a correct one was borne out by later tests at much higher temperatures than 300° F.

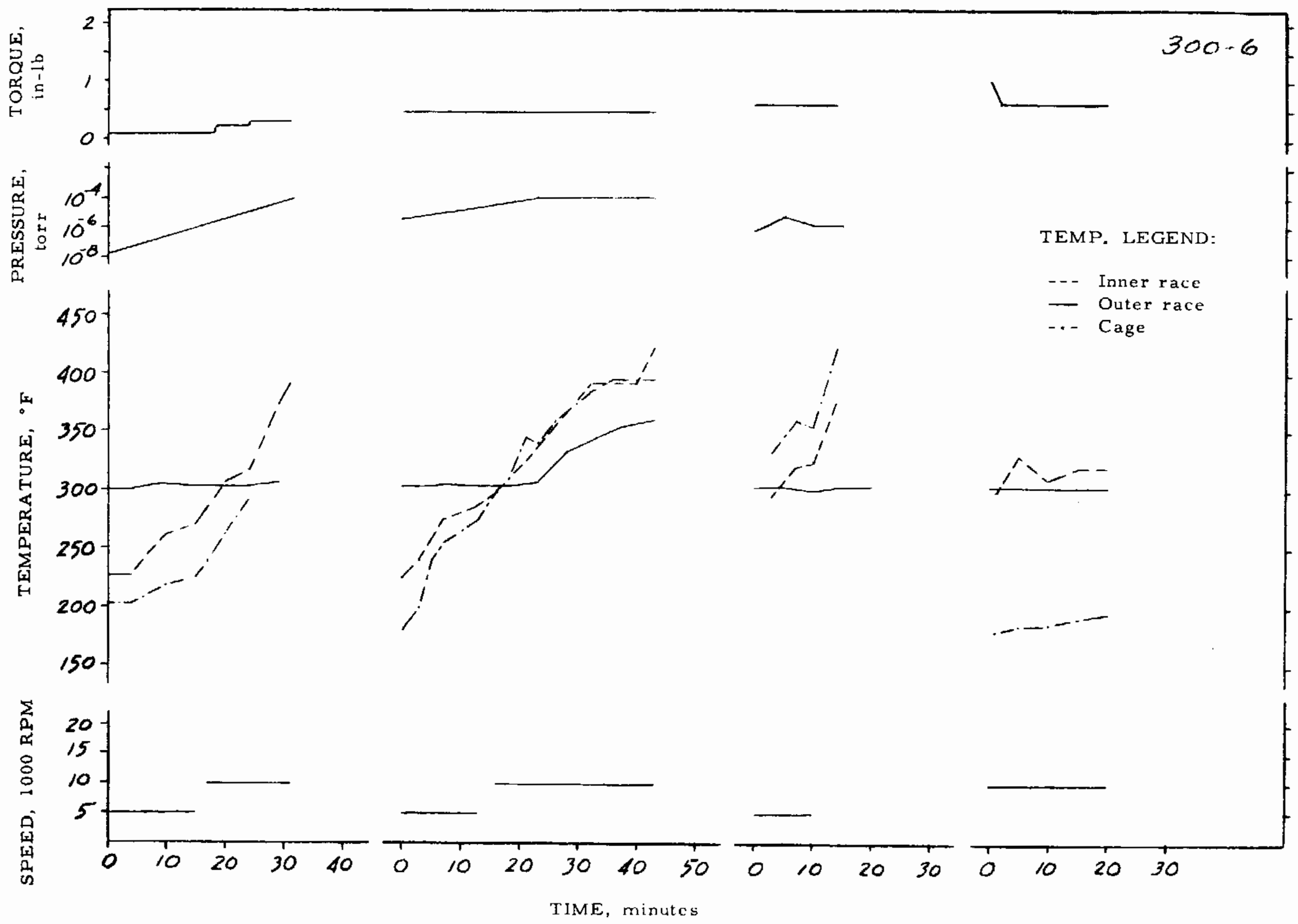


FIGURE 15. PERFORMANCE CURVES FOR TEST 300-6

Test 300-7

Nominal test temperature: 300° F

Bearing: 204 R-ST-46, Serial 8A, dated 1/65

Cage: MoS_2-epoxy compact, machined

Contact angle: 25 lb thrust, before test, 35° 7'

Cage radial clearance: 0.0085 in., cage out of round by 0.0026 in.

Cage weight change: Cage completely destroyed

Final description of bearing

Cage completely destroyed, no piece larger than a pea left. Inner race lands scored. Raceway etched in single path. Some gross deposits of MoS_2. Outer raceways and lands badly scored. No pattern of pitting. Balls scratched, show few spots of metal transfer and some have very small flat spots. Burnished with MoS_2.

Test description:

This was a vacuum environment test, using the ceramic balls instead of the larger steel balls in the front support bearing. The cage and inner race temperatures of the test bearing increased rapidly to values well above those of the outer race. Torque readings displayed a considerable noise at 5000 rpm. At 10,000 rpm, the torque readings smoothed out considerably. At 42 minutes, the system gave a loud squawk and the cage follower lost synchronization. It is believed that momentarily the cage hung up and skidded the balls. The momentary cage speed change was too large to maintain follower operation. Strangely enough, the torque did not reflect any trouble although the torque was a little more erratic than usual during the minute and a half prior to cage follower drop-out.

When the speed was increased to 15,000 rpm, the outer race and inner race temperatures began to climb rapidly. The torque became very erratic and momentarily peaked at a high value. The system stalled shortly afterward.

The test bearing cage had been completely destroyed. The highest cage temperature recorded was slightly in excess of 400°F, but it is evident that after the cage follower system stopped and cage temperatures could no longer be measured, the temperature rose to very high values. The end of the drive shaft, the heat shields, the optics bank, and all parts closely adjacent to the test bearing, were completely covered with a varnish-like layer of burned epoxy and MoS_2.

The load ring, to which was attached the outer race of the bearing, had twisted in such a way that the torque arm was jammed. The three miniature thrust-loading ball bearings were broken.

Although there was no certainty that the bearing had been misaligned, there was no question that the cage had been distressed. In repairing the damage, particular attention was given to alignment. Some experimenting showed that alignment could vary between installations by a considerable amount and that in order to assure really good alignment each installation had to be checked. The institution of this policy later proved to be of real value.

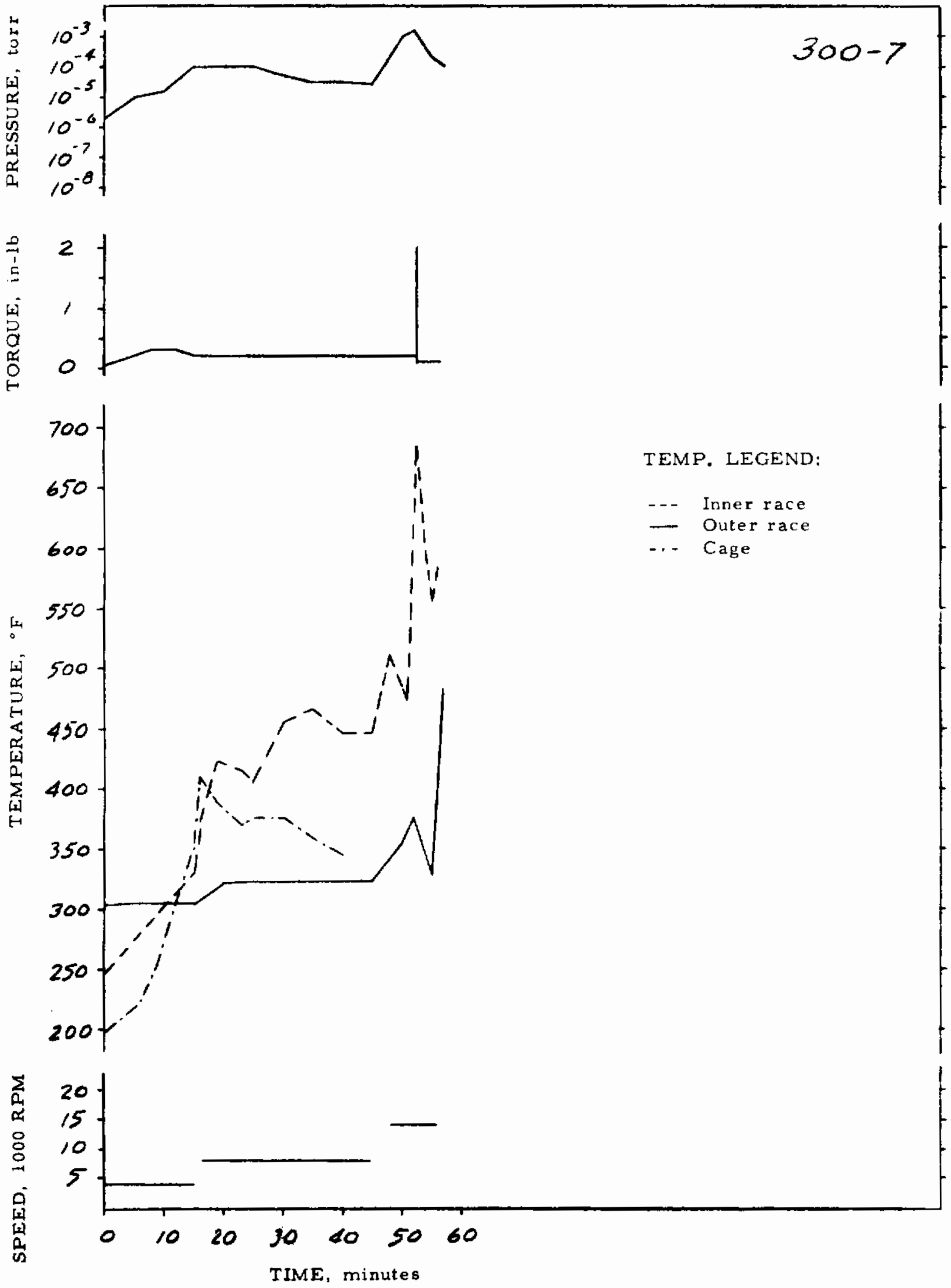


FIGURE 16. PERFORMANCE CURVES FOR TEST 300-7

Test 600-8

Nominal test temperature: 600° F

Bearing: 204 R-ST-45, Serial 5, dated 3/65

Cage: Niresist, machined, coated with MoS_2-graphite-sodium silicate film

Contact angle: 25 lb thrust, before test, 31.6°; after test, 28.6°

Cage radial clearance: 0.0035 in.

Cage weight change: 1.55% loss

Final description of bearing:

Coated inner surface of cage where it contacts the inner race lands completely worn away. Ball pocket coating worn away. Metal appears to be worn also. Outer surface of cage not touched. Inner race ball path region generally frosted but no particular path evident; all signs of coating gone. Lands scored slightly. Outer race ball path generally frosted with no particular path evident. Balls thoroughly coated with MoS_2 and varnish-like layer. When scraped, the substrate (ball) appears sandblasted.

Test description:

This run, the first of the metallic cage bearings, was in a nitrogen atmosphere.

The bearing, due to the solid film lubricant coating, did not rotate very freely, but on the other hand, the initial running torque was not much higher than that found for the previous bearings and was constant. The vibration of the outer race support ring was very much less than heretofore encountered. The cyclic nature of the torque as a function of induction heating "on" time (see also Test 300-6) was very evident from the beginning. Figure 17 shows a portion of the torque trace taken in the latter part of the test where this torque cycling is very pronounced.

The initial temperature drop across the bearing was higher than any previously tested bearing. The increase in both cage and inner race temperature was gradual until about half way through the 10,000 rpm phase. Then both temperatures skyrocketed, the cage peaking briefly at about 875° F. The torque, steadily increasing, also quickly increased and reached a very high value at which it remained until the end of the test. During most of the 10,000 rpm phase, the torque values were erratic, indicating some roughness in operation. However, a few minutes before the change to a higher speed, the bearing operation smoothed out, at however, the same average value that had continued to exist after the sudden increase at 30 minutes. It should be pointed out that by "smooth operation" is not implied a constant torque. Actually, the torque increased and decreased with induction heater cycling, but the cycles were very uniform.

At 13,000 rpm, the torque continued its uniform cycling. The inner race temperature leveled off. The cage thermocouple signals became intermittent, sometimes disappearing altogether. They had not broken, however. After 85 minutes of operation, it was decided to stop and examine the cage thermocouples, trying to explain the intermittent signal.

As the speed was decreased preparatory to stopping, the cage thermocouple signals once more came through clearly and steadily.

Their examination showed no obvious problem. The same problem had been encountered earlier (see Test 300-5) and no reason was seen at that time. After additional checks of obvious problem areas proved fruitless, the trouble was believed to exist in the connection between the ends of the cage thermocouples and their pin connections to the hermetic seal at the end of the cage follower shaft. It was surmised that at high speeds the jack on the end of the lead began to vibrate on the pin in the seal. In order to stiffen the contact between the jack and pin, the jack was coated with a high-temperature epoxy. Evidently, this was the correct solution, since the trouble never occurred again.

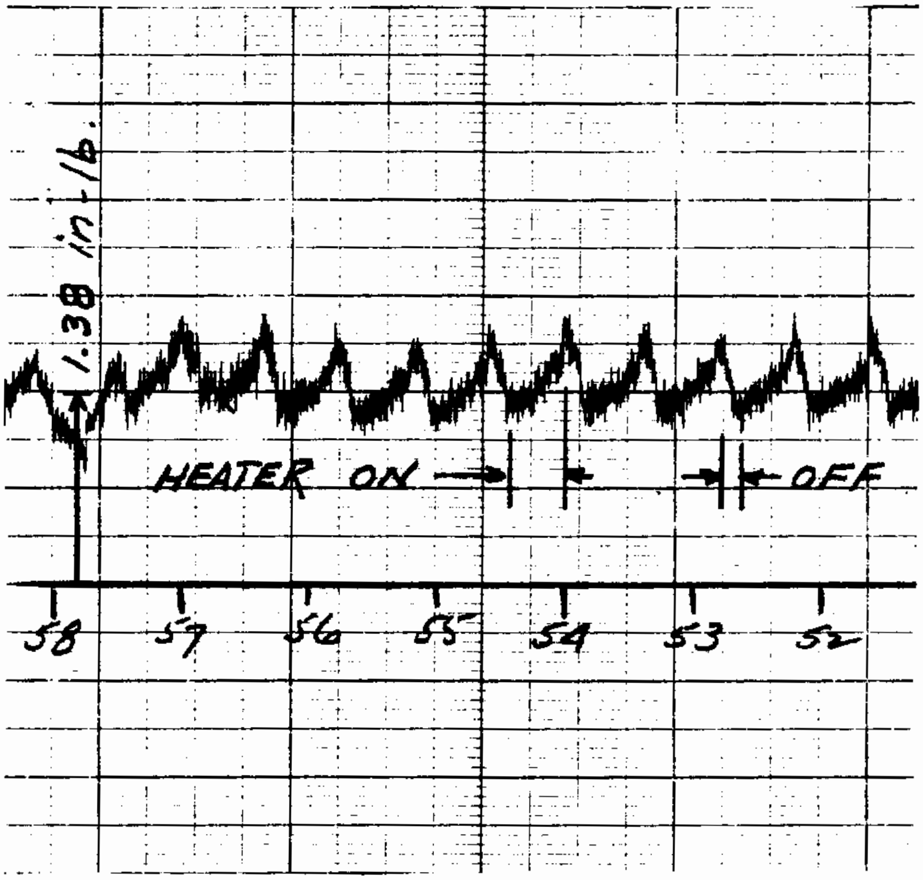


FIGURE 17. TORQUE CYCLING AS INDUCTION HEATER CYCLES ON-AND-OFF

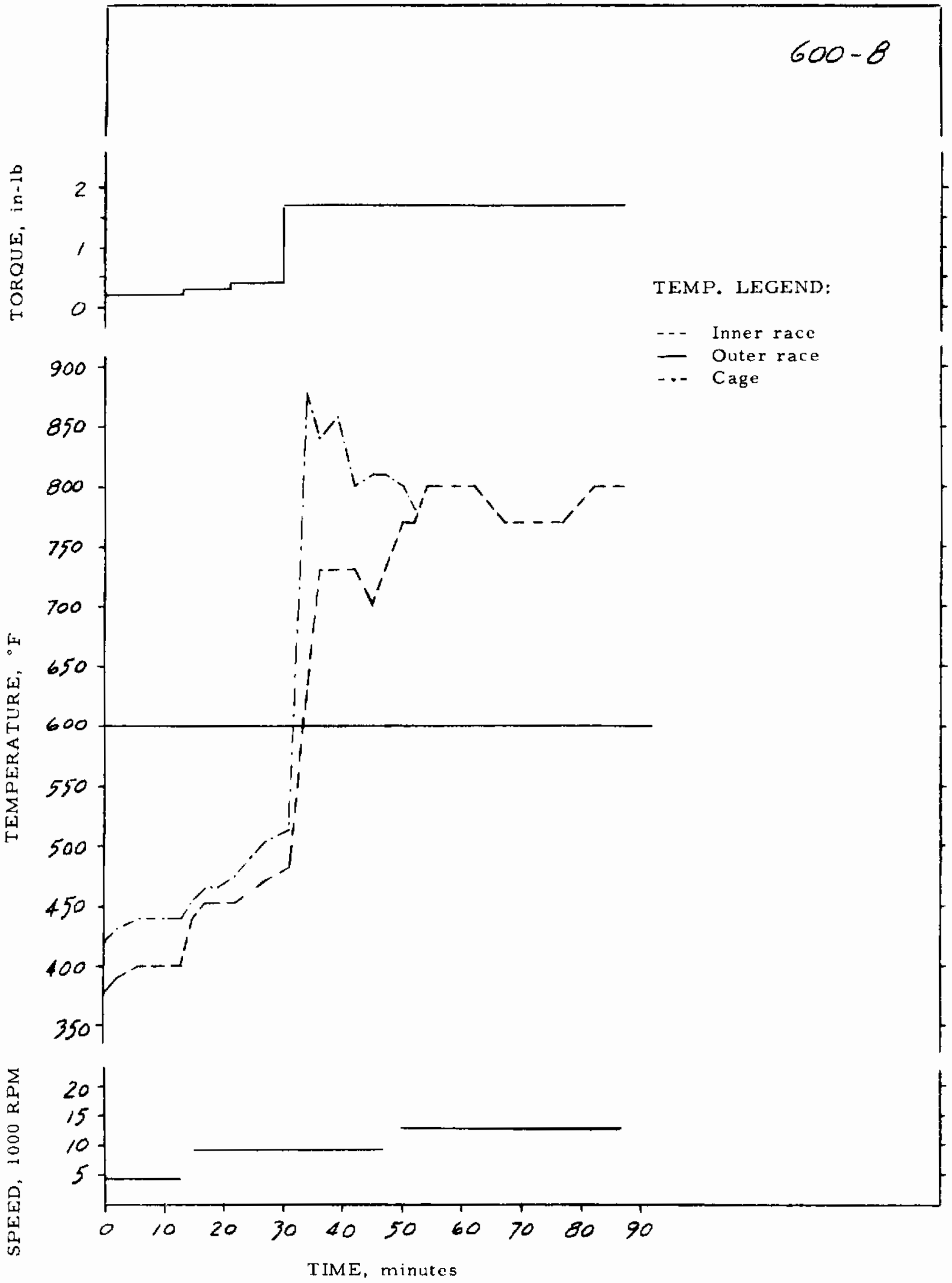


FIGURE 18. PERFORMANCE CURVES FOR TEST 600-8

Test 600-9

Nominal test temperature: 600° F

Bearing: 204 R-ST-45, Serial 8, dated 3/65

Cage: Niresist, machined, coated with MoS_2-graphite-sodium silicate film

Contact angle: 25 lb thrust, before test, 33.2°; after test, 30.1°

Cage radial clearance: 0.0021 in.

Cage weight change: 1.55% loss

Final description of bearing:

Coating rubbed off of inner surface of cage and ball pockets. Some metal wear in ball pockets. Outer surface of cage not touched. Inner raceway devoid of coating but no distinct ball path. Race lands scarred. Outer raceway clean and smooth. Balls very uniformly coated with MoS_2 and varnish-like substance that may be scraped off. The substrate (ball) is uniformly pitted like a sandblasted surface.

Test description:

This was an air environment test. The outer race was brought up to about 340° F when the test was started. The cage and inner race temperatures were nearly equal at 250° F. The outer race was heated uniformly. The cage and inner race temperatures rose almost uniformly at approximately the same rate until the outer race reached 600° F. Then the cage and inner race temperatures rapidly increased. The behavior of the cage and inner race temperatures was almost the same as in the previous test, Test 600-8.

This test had been intended to check the "fix" on the vibration of the cage thermocouple leads, so the speed was initially set at 13,000 rpm, and was maintained for slightly over 50 minutes. As the speed was increased to 19,500 rpm the cage follower lost synchronization and destroyed the cage thermocouples.

The torque was not as uniform in its behavior as in the previous test, but it was much steadier than in the early tests with the MoS_2-epoxy cages. Some of this improvement can be traced to the improved methods of bearing alignment used in these latter tests - whether all of the improvement lies in this is not known. Additional tests with the epoxy-MoS_2 cage would need to be made.

Torque readings beyond the 30-minute mark are suspect since there is a zero shift in the recording system.

The test was stopped because of excessive test bearing noise.

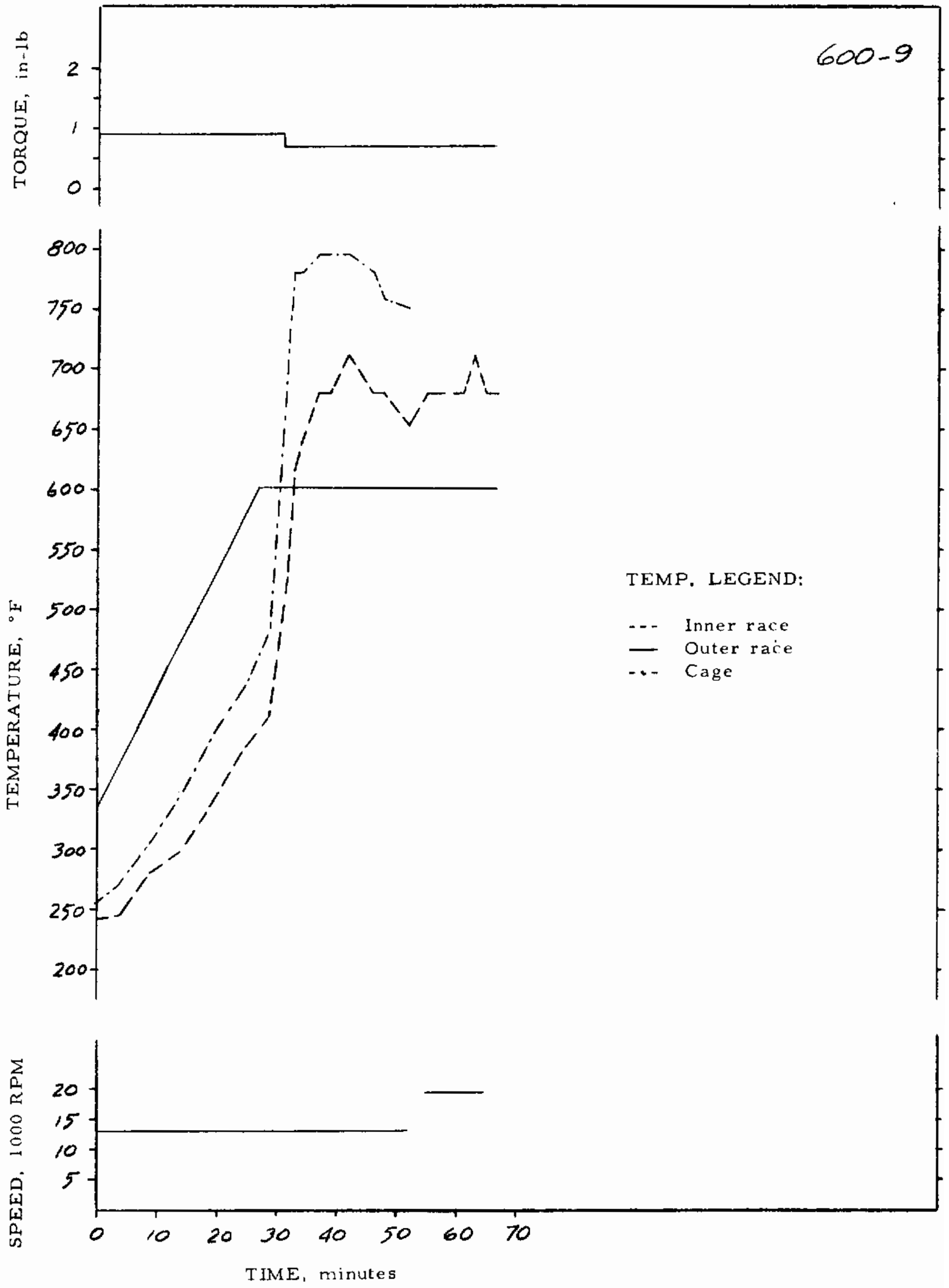


FIGURE 19. PERFORMANCE CURVES FOR TEST 600-9

Test 600-10

Nominal test temperature: 600° F

Bearing: 204 R-ST-45, Serial 3, dated 1/65

Cage: Niresist, machined, coated with MoS_2-graphite-sodium silicate film

Contact angle: 25 lb thrust, before test, 30.0°; after test, 28.4°

Cage radial clearance: 0.0018 in.

Cage weight change: 0.76% loss

Final description of bearing:

Very light wear in cage inner surface and in ball pockets. Raceways still have some coating. Balls shiny with very light layer of burnished MoS_2.

Test description:

This was a vacuum environment test. It was unusual in that the inner race and cage temperature did not rise appreciably during the entire run of 80 minutes. The torque was very constant and smooth, showing almost none of the usual vibration of the load ring.

The cage follower dropped out of synchronization shortly after reaching 13,500 rpm. When this happened, there was a sudden and considerable vibration of the rig and the torque reading became negative. The inner race temperature started dropping and finally the test was stopped.

It was expected that the miniature loading-point bearings had broken again and jammed the torque arm. When the system was opened up, no trouble could be found and there is no explanation for the abnormal behavior.

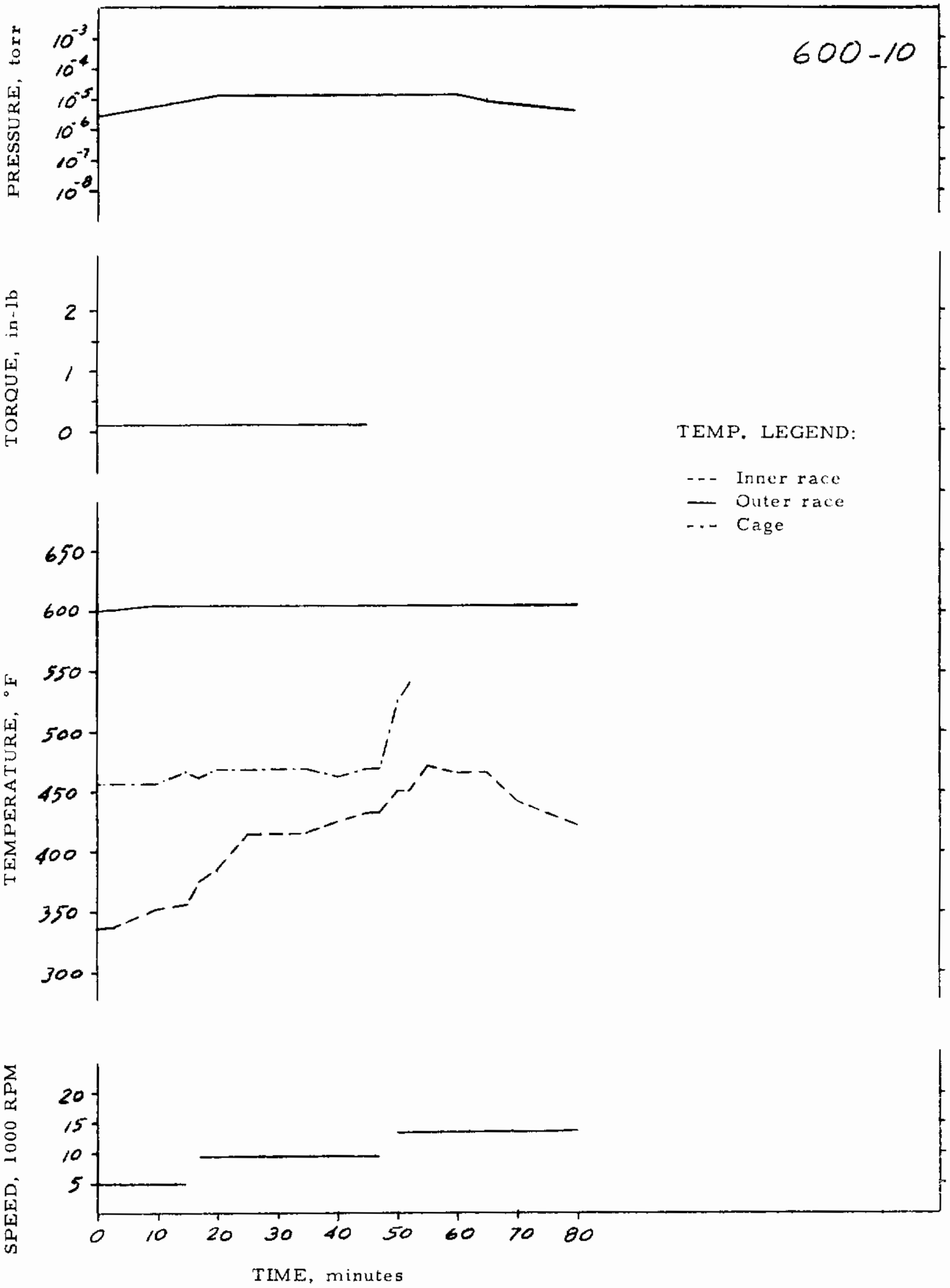


FIGURE 20. PERFORMANCE CURVES FOR TEST 600-10

Test 600-11

Nominal test temperature: 600° F

Bearing: 204 R-ST-45, Serial 13, dated 1/65

Cage: Niresist, machined, coated with MoS_2-graphite-sodium silicate film

Contact angle: 25 lb thrust, before test, 27.6°; after test, 31.6°

Cage radial clearance: 0.0022 in.

Cage weight change: 0.38% loss

Final description of bearing:

Light wear of coating on inner surface of cage; no wear on outer. Ball pockets lightly worn. Inner race coating smoothed and worn. A thin layer apparently still present. Race lands just starting to show metal contact. Outer race has thin layer of coating which may be scraped loose. Balls have very light burnished coating.

Test description:

This was a vacuum environment test. The behavior of the bearing was somewhat like that of the previous test, in that the inner race temperature did not increase very much above its initial temperature. The torque was very uniform and constant until the speed was increased to 13,500 rpm, whereupon it became quite irregular for a period of 4 minutes. The torque then settled down considerably, but not nearly as regular as it was initially. The sudden erratic torque at an increase in speed is not unusual and is, in fact, more normal than not. The bearing must have to accommodate itself to the new speed.

It will be noted that the cage temperature increased at the same time as the torque irregularity appeared.

At the end of 67 minutes of operation, the inner race thermocouple signal failed. This was due, as discovered after the test, to the rotating coil slipping off of its mount and destroying both itself and the stationary pick-up coil.

Shortly after, the cage follower dropped out of synchronization and the test was stopped.

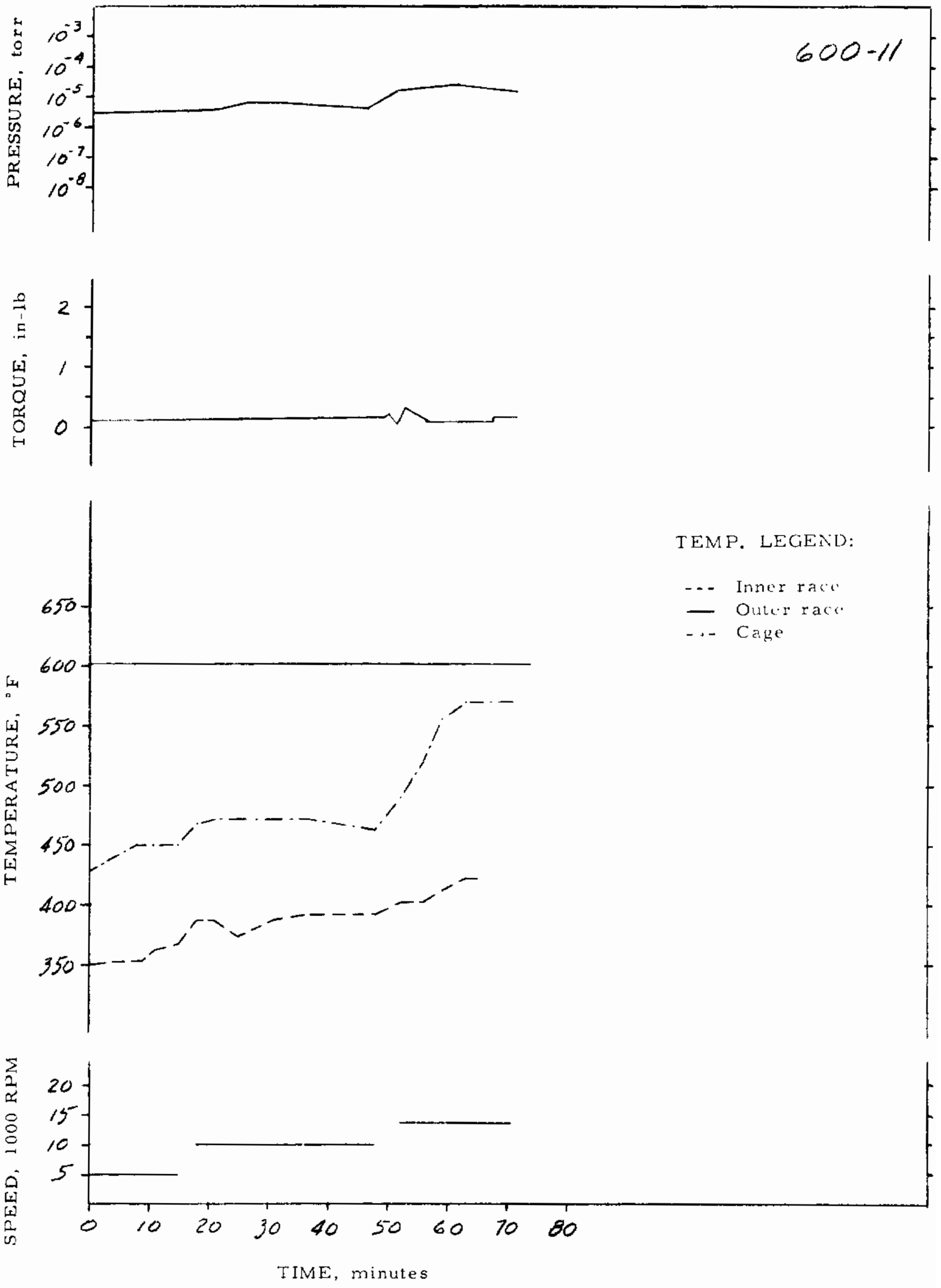


FIGURE 21. PERFORMANCE CURVES FOR TEST 600-11

Test 600-12

Nominal test temperature: 600° F

Bearing: 204 R-ST-45, Serial 12, dated 1/65

Cage: Niresist, machined, coated with MoS_2-graphite-sodium silicate film

Contact angle: 25 lb thrust, before test, 26.7°; after test, 25.8°

Cage radial clearance: 0.0028 in.

Cage weight change: 0.51% loss

Final description of bearing:

> Cage inner surface coating worn but not completely; ball pocket coating worn to bare metal. Outer surface not touched. Inner race worn to bare metal; surface burnished with MoS_2. Outer race surface frosted. Balls clean and smooth.

Test description:

> This was a vacuum environment test. The temperature behavior started out about the same as the two previous runs, Tests 600-10 and 600-11 with a small rise in the cage and inner race temperatures. The torque was irregular and very low. About the time that the speed was increased to 10,000 rpm, the outer race temperature control thermocouple began to act up and no longer controlled or measured the outer race temperature. There is little doubt that the outer race temperature increased, and rapidly. Some hit-or-miss control was attempted but there was no way to evaluate the effort. The test was continued, however, and the cage follower stopped while the shaft speed was being increased from 10,000 rpm. After 49 minutes of operation the inner race thermocouple signal failed. The rotating coil had again broken loose.
>
> After the test, the outer race temperature control thermocouple was examined to see if some reason could be found for its failure to control. The thermocouple was still intact, but it was grossly oxidized. This was traced back immediately to the shaft thermocouple telemetering system calibration which had just been performed after losing one of the rotating coils in Test 600-11 The calibration had been carried to temperatures of slightly over 1000° F, using this particular iron-constantan thermocouple Since the calibration was carried out in air, the excessive temperature had caused oxidation. The thermocouple was cleaned and checked and proved good as new.

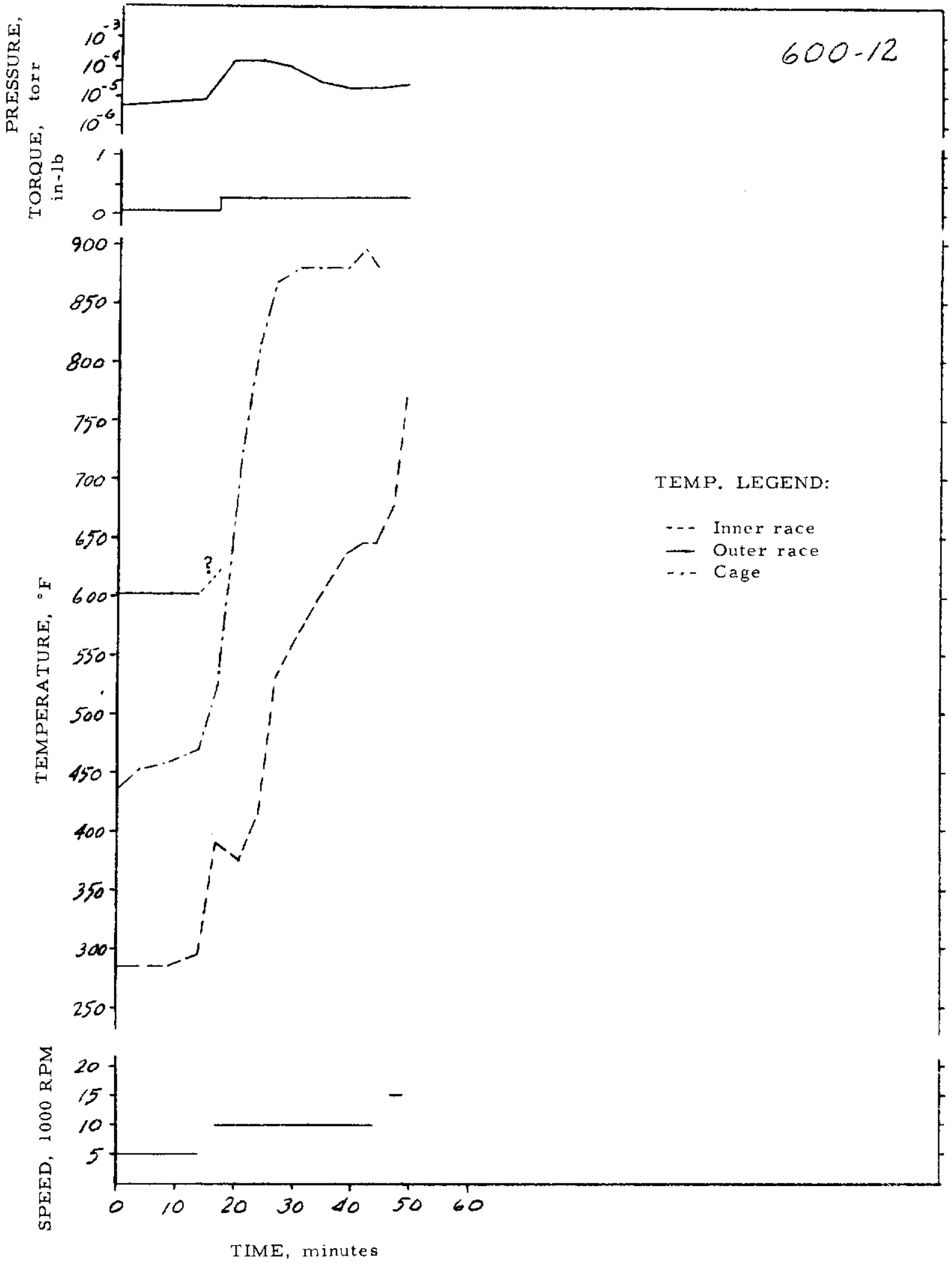


FIGURE 22. PERFORMANCE CURVES FOR TEST 600-12

SECTION VI

DISCUSSION OF RESULTS

A. The Test Facility

Probably the first question that might be asked regarding the temperature measurements is their accuracy. The temperature readings were obtained from the screen of an oscilloscope, with a maximum signal height of 6 cm. The choice of amplifier attenuation was usually made so as to obtain the largest signal amplitude possible; this being on the average, 3 cm peak-to-peak. If the signal were steady (and this was unfortunately not always the case), it was easily possible to read the amplitude to 0.1 cm. At an attenuation of 0.2 mv/cm, this meant a possible error in reading of ± 0.02 mv. This error could mean, in the case of cage temperature measurement, an error of ± 24°F at 1000 rpm cage speed (approximately 2500 rpm inner race speed) or ± 7°F at 5000 rpm cage speed (about 12,500 rpm inner race speed). The inner race temperature error for the same ± 0.02 mv reading error would be ± 10°F for any speed above the lowest calibrated, 4000 rpm.

For smaller values of the attenuation, as for example 0.05 mv/cm, the error in reading the oscilloscope would still be ± 0.1 cm, but this would now represent only ± 0.005 mv, or ± 6°F for the cage at 1000 rpm, the worst case.

Because the calibration could not be done with complete assurance that the signal photographed and subsequently analyzed was that temperature read by the reference measurement devices, the calibration curve is not drawn point-to-point. Instead it is faired, with an effort made to not deviate from any point more than the expected error for that speed and attenuation at which the signal was taken.

One measure of the "validity" of the calibration could be seen when, for example, the inner race temperature were being read at 5000 rpm and the speed were raised to 10,000 rpm. Would the two signal amplitudes at the two different speeds give the same temperature reading? This was so in some cases and not in others; and in these latter cases the change was consistent with the overall rising or falling trend of the temperature. Also, if the temperature reading for the inner race did change upon change in speed, the same type of change was most often noted also in the cage temperature and this is a completely separate system in all respects. It is believed that the temperatures of cage and inner race presented in the data are more than representative of trends and are within ± 15°F.

The cage follower is a critical system. The present drive motor is marginal in power, so that shaft resonance and grossly uneven light signals reflected from the cage may cause the cage follower to lose synchronization. Unfortunately, this action destroys the cage thermocouples.

Vacuum levels in the test chamber have been disappointing. The best level attained has been 2×10^{-8} torr, with the bearing stationary. Bakeout is definitely limited, since radiation from the chamber walls heats the optics block. The photocells in the optics block are limited to about 225°F. Severe cleaning, either chemically or abrasively is not generally possible although moderate cleaning, such as solvent degreasing and alcohol rinsing is possible for some parts.

When the bearing is running, the amount of vapor given off is quite large and system pressures rise into the 10^{-5} torr range. In this range, the ion pump pumping rate drops off and it has been the experience that the diffusion pump proves a better choice for maintaining a vacuum under these conditions.

B. Test Bearings

One of the more interesting observations of these tests was the high temperature of the cage, often higher than that of the inner race. This was true regardless of whether the cage were of a relatively poor heat transfer material such as epoxy or of a high heat transfer material such as nickel cast iron. The cage may receive heat by conduction from the balls and its piloting surfaces. In the case in point, these pilot surfaces were on the inner race. It also receives heat as a result of friction between these aforementioned surfaces. Cage heat is lost between these same surfaces, and if operated in air, is lost by forced air convection, until equilibrium is reached.

The inner race is heated by the flow of heat from the outer race through the balls. Also, friction between the balls and the inner race and the cage introduce additional heat. In the particular design of the test rig, the test bearing drive shaft presented a small cross section through which heat could flow out of the shaft. Hence, the inner race temperature tended to become high, usually higher than the outer race temperature. In those few cases where the test was continued long enough, the inner race temperature leveled out and was higher than the outer race (see Tests 300-5, 600-8, 600-9). Although the cage temperature could not be measured throughout these tests, there is evidence that it eventually stabilized at about the same temperature as the inner race. Neither of these three tests mentioned above were in a vacuum, and no vacuum tests continued long enough to be able to say that equilibrium had been reached. Hence relative order and severity of temperature stability cannot be made.

Some of the 300°F test bearing balls were lightly to moderately coated with MoS_2, while others, tested under roughly equal conditions, were not. There is no explanation for this. However, in those cases where the ball was so coated, the race and ball pitting were small compared to the situation where the balls had not picked up the MoS_2. Clearly, the presence of the MoS_2 reduced the contact wear. Tests in which the balls became coated were those that early suffered some problems that tended to wear the cage rapidly. Perhaps the MoS_2 released had a beneficial effect.

The value of loose MoS_2 in reducing wear was most noticeable in the 600°F bearings. Here the coating on the balls was heavy and they showed no pitting. They did look, however, where the coating was scraped off, as if they had been lightly sandblasted. The races were uniformly frosted, without the distinct tracks of large pits found in the 300°F bearings. By and large, these 600°F bearings were in much better condition than the 300°F ones.

Fracture in the MoS_2-epoxy cages appeared to be a problem which might be a limit to their high-speed usefulness. However, the test facility used two 205-size angular-contact ball bearings for drive shaft support and these bearings had the same type of epoxy cages. Their operation was very satisfactory. The coated metal cages, while performing well during testing, lost all of the coating on their rubbing surfaces. Probably these bearings would have begun to fail by metallic wear after a short while.

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13. ABSTRACT

Operation of a facility for measuring cage and inner race temperatures of lightly-loaded 20 -mm angular-contact ball bearings at high speed and vacuum is described. Results of tests on 440C ball bearings with MoS_2-epoxy compact cages at 300°F and with Niresist cages coated with MoS_2-graphite-sodium silicate solid film at 600°F are given. The latter bearings, for the short (about 1 hour) test time, ran smoother and with less raceway damage than did the bearings with the epoxy-MoS_2 cages.

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It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.