N78-26445

# NASA TECHNICAL MEMORANDUM

NASA TM-78935

NASA TM-78935

# SOME LOAD LIMITS AND SELF-LUBRICATING PROPERTIES OF PLAIN SPHERICAL BEARINGS WITH MOLDED GRAPHITE FIBER REINFORCED POLYIMIDE LINERS TO 320° C

by Harold E. Sliney
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at the
Joint Lubrication Conference
cosponsored by the American Society of Mechanical Engineers
and the American Society of Lubrication Engineers
Minneapolis, Minnesota, October 24-26, 1978

# SOME LOAD LIMITS AND SELF-LUBRICATING PROPERTIES OF PLAIN SPHERICAL BEARINGS WITH MOLDED GRAPHITE FIBER REINFORCED POLYIMIDE LINERS TO 320° C

by Harold E. Sliney

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-9678

## ABSTRACT

Plain spherical bearings with molded liners of self-lubricating graphite fiber-polyimide composite were developed and their dynamic load capacities were determined. Liners were prepared by transfer molding a prepolymer resin-fiber mix into the space between the ball and outer race, then completing polymerization under heat and pressure. Bearing dynamic load capacities were in excess of 140 MPa (20 000 psi) from room temperature to 260° C and about 70 MPa (10 000 psi) at 320° C. Friction coefficients were about 0.20 at room temperatures and light loads and tended to decrease with increasing temperatures and loads to about 0.15. Thermal expansion of the liner at uniform bearing temperatures of 200° C or higher produced a bearing preload which could be alleviated by providing an initial internal diametral clearance of 0.05 to 0.10 mm.

## INTRODUCTION

Plain spherical bearings are important in applications requiring oscillating motion and self-aligning capability. Aircraft applications include airframe control surface bearings and bearings for engine control linkages. Plain spherical bearings are commonly self-lubricated with a reinforced PTFE liner bonded to the spherical seat of the outer ring (1, 2). This is a satisfactory material with high load carrying capacity to a maximum temperature of about 165° C. For higher temperatures, a promising alternative self-lubricating liner material is bonded, graphite fiber reinforced polyimide (GFRPI) (3-5). Polyimide composites retain essentially room temperature mechanical strength to about 260° C and a reduced, but significant strength to about 340° C (6). In this program experimental or plain spherical

STAR Category 37

bearings with bonded GFRPI liners were tested to 320° C.

One of the most important requirements of plain spherical bearings for aircraft control surface bearings is a high dynamic load capacity usually in excess of 69 MPa (10 000 psi). Therefore, in this study, the emphasis was on the experimental determination of bearing dynamic load carrying capabilities.

Plain spherical bearings, with a molded GFRPI spherical element and a 440C-HT steel outer ring (fig. 1) were previously shown to have useful dynamic load capacities of 69 MPa (10 000 psi) at room temperature and 25 MPa (3600 psi) at 340° C. The bearing design used in the present study (fig. 2) employs GFRPI as a self-lubricating liner, 0.0015 m (0.060 in.) thick, bonded to the spherical seat of the outer race. The spherical element and outer ring are both 440C-HT steel. Duplicate load capacity tests were run at each of four temperatures: room, 200°, 260°, and 320° C; bearing oscillation was ±15° at a frequency of 0.4 hertz. Bearings were run at increasing loads until failure occurred. In these tests, bearing torque was continuously monitored.

## BEARINGS

The plain spherical bearing design is shown in Figs. 1 and 2. Figure 1 is the design of bearings reported in Ref. 4. The ball is a molded composite of GFRPI. The bearing is assembled by fitting the split outer ring sections around the ball then fastening them with a snap ring. The bearings used in the present study are shown in Fig. 2. The ball and outer race are both 440C-HT steel. The ball is hardened to Rockwell C-60 and has a polished surface finish of $10^{-7}$ m (4 $\mu$in.) rms. The GFRPI composite is used as a self-lubricating liner which is bonded to the outer race. A cross section of the test bearings and the principal bearing dimension are shown on Fig. 3.

## COMPOSITE MATERIAL

The self-lubricating bearing liners consist of a 1:1 ratio by weight of polyimide resin and chopped graphite fibers.

The resin used in the composite bearing material is an addition-type polyimide. Addition polymers consolidate during a final cure by a polymerization reaction which does not release volatile reaction products. The more conventional condensation-type polyimides consolidate during the cure by a reaction which releases large volumes of volatile matter, predominantly water vapor. The necessity of disposing of volatiles makes it difficult to achieve a dense, cured polymer body without voids. The addition type polymer was therefore used in order to avoid this problem.

The graphite is in the form of chopped fibers $6.4\times10^{-3}$ m (1/4 in.) long, with an equivalent diameter of $7.6\times10^{-6}$ m (0.00003 in.) and a specific gravity of 1.4. The fibers have a tensile strength of 600 MPa (90 000 psi). The composite has a composite yield strength of about 200 MPa (30 000 psi) and an elastic modulus 4.4 GPa (640 000 psi). The coefficient of thermal expansion in the $25^{\circ}$ to $300^{\circ}$ C range is $25.6\times10^{-6}$ cm/cm-$^{\circ}$C.

The molded liners were made by transfer molding the graphite fiber polyimide resin mix into the space between the ball and race, then completing the polymerization under heat and pressure. During the molding and polyimerization procedure, the ball and race were mounted with accurate concentricity and they functioned as the main elements of the molding fixture. The ball was precoated with a mold-release to minimize adhesion between the ball and the composite.

The molding procedure consisted of: (1) randomly mixing the chopped fibers with the polymer precursor solution (unpolymerized resin dissolved in a solvent); (2) evaporate solvent for 1 hour at $200^{\circ}$ C; (3) precure (B-stage polymerization) for 1 hour at $230^{\circ}$ C; (4) mold under heat and pressure for 1 hour at $320^{\circ}$ C and 69 MPa (10 000 psi), then hold at pressure and cool to $260^{\circ}$ C before releasing mold; and (5) post cure 4 hours at $200^{\circ}$ C. The bearings were fabricated and tested by a commercial bearing manufacturer.[1]

## BEARING TEST MACHINE AND PROCEDURE

The bearing test machine was fully described in Ref. 7 and is shown schematically in Fig. 4. Briefly, the machine is capable of applying bearing radial loads in excess of 62 300 N (14 000 lb). Two test bearings are loaded against each other on opposite sides of a friction drive. A crank mechanism provides reciprocating motion to the

[1]Marlin Rockwell Division of TRW, Jamestown, N.Y.

drive mechanism which in turn induces bearing oscillation. Bearing torque is measured by strain gages mounted on the drive rod. It is important to note that the bearing spherical element is held stationary and the outer ring oscillates. Therefore, the location of maximum stress is stationary on the ball but moves cyclically on the composite liner over the amplitude of the bearing. This arrangement is probably less severe than a test arrangement in which the ball oscillates against a stationary outer ring and a small area of the liner is constantly subjected to the stress maximum. Bearing heating is provided by an oven which encloses the bearing assembly.

Bearing radial wear is indicated during the tests by means of dial gages suitably mounted on the test machines. The dial gages indicate any changes in the eccentricity of the bearing. Changes in dial gage readings are used as an indication of wear only during bearing operation at constant load in order to eliminate the effect of deflections of the test machine.

The bearing test conditions were:

| | |
|---|---|
| Oscillation rate | 0.4 hertz |
| Oscillation amplitude | $\pm 15^{\circ}$ |
| Test temperatures | room temperature (no external heat), $200^{\circ}$, $260^{\circ}$, and $320^{\circ}$ C |
| Load | step loads increasing in increments of 2200 N (500 lb) at intervals of 5 minutes |
| Duration | until failure of at least one bearing in the test |

The failure load is here defined as the load at which the liner fractures or a large disproportionate increase in wear rate or deformation occurred.

## RESULTS AND DISCUSSION

### Load Capacity

Table I summarizes the dynamic load capacities of GFRPI-lubricated plain spherical bearings at four different temperatures. Two bearing tests were performed at each temperature and the reproducibility of the load capacities was excellent. Load capacity was 160 MPa (23 000 psi) at room temperature and at $200^{\circ}$ C (slightly higher in one test) corresponding to a radial load of 62 300 N (14 000 lb) for this size bearing (projected area = 28.6 mm (1.125 in.) ball diameter × 13.7 mm (0.54 in.) race width = 394 $mm^2$ (0.61 $in^2$). A reduction in permissible loading of about 10 percent from the above values is indicated for bearing operation at 260° C load capacity at 320° C is 40 to 45 percent of the room temperature capacity, but is still appreciable, corresponding to a radial load of about 26 700 N (6000 lb).

The data from Table I are plotted in Fig. 5. Data from Refs. 5 and 7 are included for comparison. The comparison shows that employing the self-lubricating composite as a liner bonded to the outer race is clearly better than employing it as the ball material if the application requires high load capacity. However, the GFRPI-lined bearings still do not have as high a load capacity as the plain cylindrical GFRPI bearings.

The cylindrical bearings were described in Ref. 5; they had the same wall thickness of 1.5 mm (0.060 in.) as the liners in the plain spherical bearings, but were much smaller with one-tenth the projected area of the spherical bearings. The cylindrical bearings had unit load capacity of 280 MPa (40 000 psi) which exceeds the simple compressive yield strength of unsupported composite.

It is expected that a 280 MPa (40 000 psi) load capacity can also be achieved with the plain spherical bearings with changes in bearing design to improve liner retention. This expectation is based on the observed failure mode of the bearings at their load limit: failure occurred by ejection of the liner material from the sides of the bearing during oscillation at the load limit. It is likely that retention of liner material at high dynamic load can be improved by employing a liner cross section that is thinner at the edges than at the center so that the liner material is literally wedged within the bearing.

## Bearing Torque

Bearing torque was measured continuously during the tests. The bearings were manufactured with a zero internal clearance and a negligible preload. Therefore, the bearing load during room temperature tests was entirely due to the mechanically-applied radial load. In the elevated temperature tests, however, differential thermal expansion of the GFRPI liner, which has a higher expansion coefficient than the 440C bearing steel, produced a thermally-induced preload on the bearing.

The above effect is illustrated in Fig. 6 which gives bearing torque as a function of radial load at room temperature and at $320^{\circ}$ C. The torque curve for the room temperature test is linear over the first 17 600 N (4000 lb) and passes through the origin indicating a zero preload in the bearing. The $320^{\circ}$ C curve for a bearing with zero initial internal clearance, on the other hand, intersects the ordinate at about 34 mN (300 in-lb) of torque indicating a considerable thermally-induced bearing preload. The other curve for a $320^{\circ}$ C test shows that providing a 0.13 mm (0.005 in.) initial internal clearance completely eliminated the preload. Both curves for the $320^{\circ}$ C tests have essentially the same slope indicating both bearings had the same friction coefficients. It has also been observed in previous programs that sufficient internal clearance can be maintained in the bearings operating at elevated temperatures if an adequate positive radial temperature gradient (where the outer race is hotter than the ball) exists in the bearing.

Friction coefficients calculated from torque data, corrected where necessary for bearing preload were in the range of 0.15 to 0.25. Friction coefficients tended to be at the low end of this range at the higher loads and bearing test temperatures.

Estimation of clearance requirements. - A static test was performed on a bearing that had been reworked to produce a 0.0038 cm (0.0015 in.) internal clearance. The bearing was heated in steps, then checked for internal clearance and freedom of motion with no applied load. The results were as follows:

| Temperature, $^{\circ}$C | | Radial clearance, cm (in.) | Observation |
|---|---|---|---|
| Actual | Rise | | |
| Room | 0 | 0.0038 (0.0015) | Turned freely |
| 93 | 73 | .0025 (0.0010) | Turned freely |
| 120 | 100 | .0018 (0.0007) | Turned freely |
| 150 | 130 | .0005 (0.0002) | Stiff |
| 177 | 157 | 0 | Locked |
| 204 | 184 | 0 | Locked |

Interpolation of the above data shows that clearance was lost at about 170° C or a temperature rise of 150° C. This suggests that for 320° C operation a minimum initial clearance of 0.0076 cm (0.003 in.) would have been necessary to prevent thermally-induced preload.

It is interesting that in this program, the load capacities at elevated temperature were not adversely affected by the thermally-induced preloads. The only observed effect was the higher bearing torque - also, positive radial temperature gradients, liner deformation, and wear all tend to relieve the preload. Therefore, bearings with zero initial clearance may be used when: (1) high friction coefficients during early operation at light loads can be accepted or (2) when the bearing outer ring is significantly hotter than the ball and thereby offsets the higher thermal expansion of the GFRPI liner.

## SUMMARY OF RESULTS

The dynamic load capacities and the torque characteristics of plain spherical bearings with molded graphite fiber reinforced polyimide (GFRPI) liners were determined. The GFRPI composite consisted of a 1:1 weight ratio of chopped graphite fibers and a polyimide resin. The test bearings had an outside diameter of 36 mm (1.44 in.) and a bore diameter of 15.9 mm (0.625 in.). Testing which was in the oscillatory mode with an amplitude of ±15° at 0.4 hertz, gave the following results.

1. The dynamic load capacities of the bearings were above 140 MPa (20 000 psi) from room temperature to 260° C and about 70 MPa (10 000 psi) at 320° C.

2. Friction coefficients averaged about 0.20 at room temperature and light loads and tended to decrease moderately to about 0.15 at the higher loads and temperatures.

3. Because the composite liner has a higher thermal expansion coefficient than the steel ball and outer race, differential thermal expansion of the liner imposed a preload on the bearing during the elevated temperature tests. This can be alleviated where necessary by suitably increasing the initial internal clearance of the bearing.

## REFERENCES

1. Air Force Systems Command Design Handbook 2-1, Airframe Chapter 6, "Airframe Bearings," April 1, 1971.
2. Jakobsen, K., "Oscillatory Journal Bearings," Tribology Handbook, ed. by M. J. Neale, Wiley, 1973, Section A-12.
3. Lancaster, J. K., "The Effect of Carbon Fiber Reinforcement on the Friction and Wear of Polymers," Brit. J. Appl. Phys., Series 2, 1, 549-559 (1968).
4. Sliney, H. E., and Johnson, R. L., "Graphite Fiber Polyimide Composites for Spherical Bearings to 340° C (650° F)," NASA TN D-7078, 1972.
5. Sliney, H. E., and Jacobson, T. P., "Performance of Graphite Fiber Reinforced Composites in Self-Aligning Plain Bearings to 315° C," Lubr. Eng., 31 (12), 609-613 (1975).
6. Hanson, M. P., and Serafini, T. T., "Effects of Thermal and Environmental Exposure on the Mechanical Properties of Graphite/Polyimide Composites," NASA TN D-6604, 1971.
7. Sliney, H. E., Jacobson, T. P., and Munson, H. E., "Dynamic Load Capacities of Graphite Fiber Polyimide Composites in Oscillating Plain Bearings to 340° C," NASA TN D-7880, 1975.

TABLE I. - DYNAMIC UNIT LOAD CAPACITIES

[Projected contact area: $3.94 \times 10^{-4}$ $m^2$ (0.61 $in^2$) (ball diameter × race width).]

| Temperature, °C (°F) | Load, MPa | Capacity, psi |
|---|---|---|
| Room temperature | 160 | 23 000 |
| | 160 | 23 000 |
| 200 (400) | 166 | 23 800 |
| | 160 | 23 000 |
| 260 (500) | 137 | 19 700 |
| | 148 | 21 300 |
| 320 (600) | 63 | 9 000 |
| | 74 | 10 700 |

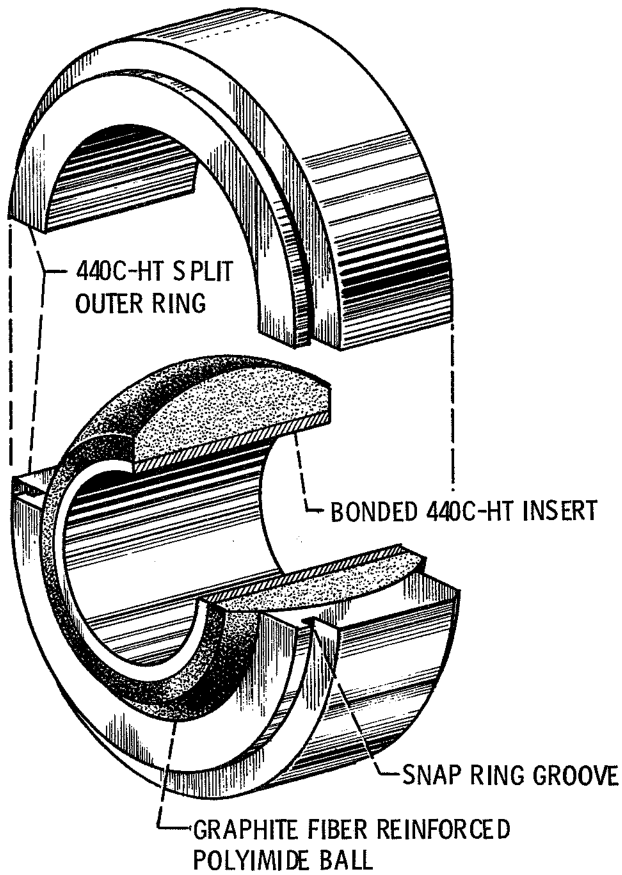


Figure 1. - Test bearing with composite ball used in reference 4 program.

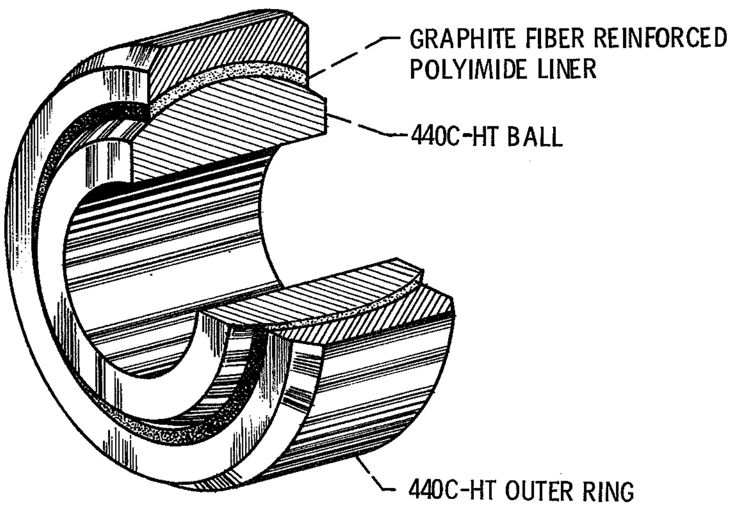


Figure 2. - Test bearing with molded GFRPI liner.

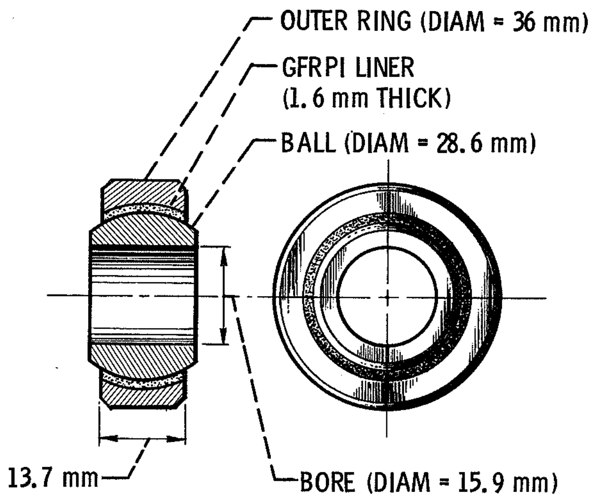


Figure 3. - Test bearing dimensions.

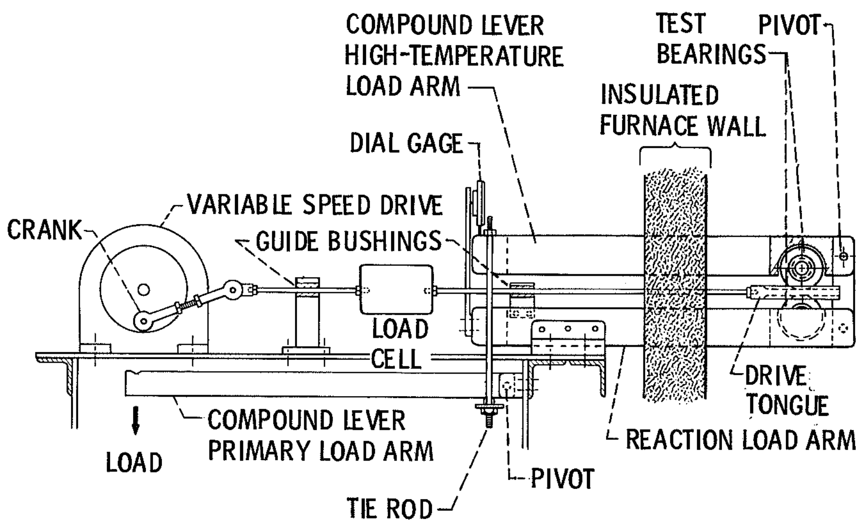


Figure 4. - High-temperature oscillating bearing test rig (high load capability).

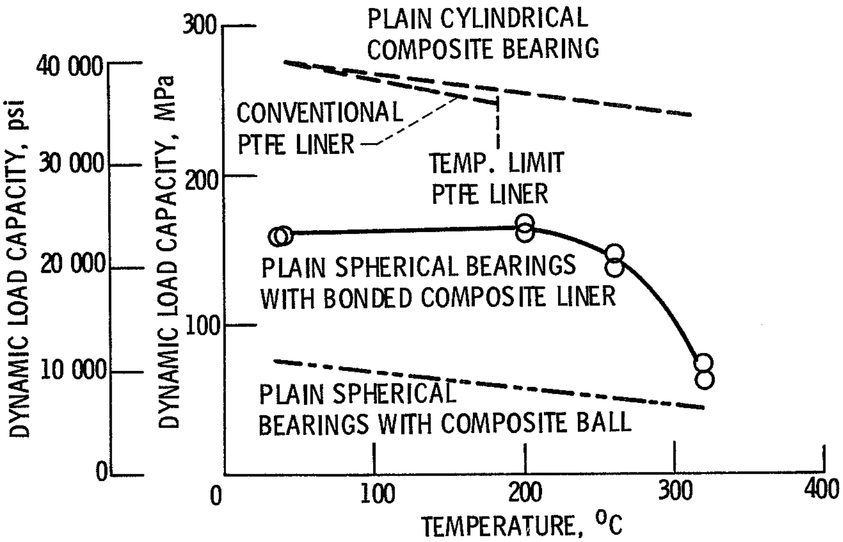


Figure 5. - Dynamic unit load capacities of three bearing designs self lubricated with GFRPI composite.

E-9673

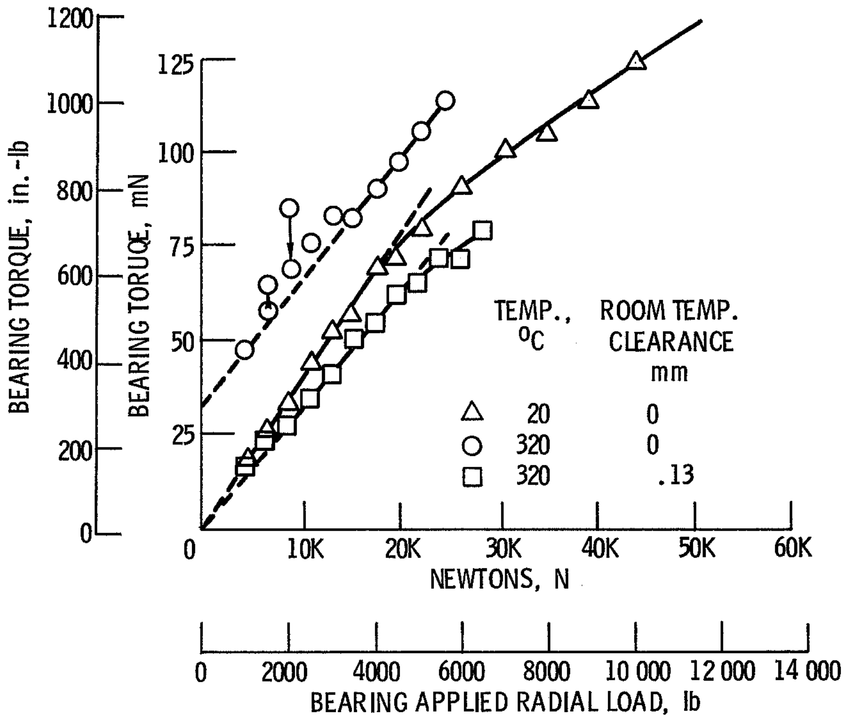


Figure 6. - Effect of load and clearance on bearing torque at 20° and 320° C.