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THE IN-VACUO TORQUE PERFORMANCE OF DRY-LUBRICATED BALL BEARINGS AT CRYOGENIC TEMPERATURES

S. G. Gould* and E. W. Roberts*

ABSTRACT

The performance of dry-lubricated, angular contact ball bearings in vacuum at a temperature of 20 K has been investigated, and is compared with the in-vacuo performance at room temperature. Bearings were lubricated using dry-lubrication techniques which have previously been established for space applications involving operation at or near room temperature. Comparative tests were undertaken using three lubricants, namely molybdenum disulphide, lead, and PTFE. It was observed that the mean bearing torque and torque noise of bearings lubricated with either PTFE or molybdenum disulphide increases with cryogenic cooling (down to 20 K). In contrast, bearings fitted with lead-containing cages (ball retainers) and lubricated with ion-plated lead films show no deterioration, in that torque levels remain unaffected on decreasing the temperature from 300 K to 20 K.

INTRODUCTION

The development of cryogenically cooled spacecraft mechanisms has created a requirement for efficient lubrication in vacuum at very low temperatures. Only solid lubrication is practicable under these conditions as oils and greases solidify at temperatures well above the cryogenic range, and the viscosities of cryogenic fluids are too low to generate sufficient load carrying capacity [1]. However, at present there exists a lack of basic tribological data upon which cryo-mechanism designers can base a reasoned choice of lubricant. Over the next few years, several space missions are planned which depend on instruments which require cryogenic cooling. These instruments include infrared detectors, superconducting devices, and a variety of "telescopes" - infrared, X-ray, gammma-ray, and high energy. Infrared detectors are of particular importance in both astronomy and Earth applications instruments. Future missions include the Infrared Space Observatory (ISO), the Far Infrared Space Telescope (FIRST), and the Upper Atmosphere Research Satellite (UARS).

Depending on their particular application, many low temperature devices contain moving mechanical parts in which pure sliding or rolling-with-sliding contacts occur (as in screw threads and ball bearings respectively). These components must be lubricated to ensure their proper operation. While it is known that molybdenum disulphide (MoS_2), lead, and polytetrafluoroethylene

*European Space Tribology Laboratory, UKAEA, Risley, Warrington, U.K.

(PTFE) are effective lubricants under vacuum at or near room temperature, their frictional properties in vacuo at very low temperatures have been little studied.

The research described in this report was carried out in order to assess the performance at cryogenic temperatures of the three main types of solid lubricant, with a view to applying them to cryogenically-cooled spacecraft instruments [2,3]. Mechanisms in these instruments typically operate under light loads at rotation rates on the order of 1 rpm per 10^4 rotations. This research is believed to be the first systematic investigation of the performance of lubricants for ball bearings operating in vacuum at temperatures below 20 K.

LUBRICANTS TESTED

There are three classes of solid lubricant: soft metals, lamellar solids, and polymers. The most commonly employed space lubricants of each of these classes are lead, MoS_2, and PTFE respectively. Typical "torque bands" for 20 mm bore angular-contact ball bearings lubricated with each of these lubricants are shown in Figure 1 [4]. These values represent room temperature torque measurements made on bearing pairs, axially loaded to 40 N and rotated at speeds of up to 200 rpm in high vacuum. Torque values are presented in terms of bands because, in addition to the torque noise, the performance of similarly lubricated ball bearings is observed to vary from component to component.

Each of these lubricants has been tested in the same size bearings operating in vacuum at temperatures below 20 K. The methods used to apply each lubricant are now discussed individually.

PTFE (Duroid)

The PTFE lubricant film was applied by using a self-lubricating cage constructed from a PTFE/chopped glass-fiber/MoS_2 composite (trade name Duroid). On rubbing against bearing surfaces, this cage produces, and replenishes, a thin "transfer film" of PTFE. Those surfaces which are not in direct contact with the cage are lubricated by means of film transfer via the balls. Thus, in the first instance the bearing is effectively unlubricated and a "run-in" is required before an effective transfer film can be established.

Lead

Lead films of approximately 0.5 microns thick were deposited onto the inner and outer raceways of test ball bearings by the technique of ion plating. The balls were not coated. Each bearing was fitted with a cage manufactured from lead-impregnated bronze, the lead within the cage serving to supplement the lead film lubricant applied to the raceways.

Figure 1 indicates that pairs of 20 mm ball bearings lubricated in this manner and subjected to an axial load of 40 N exhibit, on initial running in vacuum, torque levels of between 10 and 20 x 10^{-4} Nm. The torque increases to between 15 and 30 x 10^{-4} Nm during the running-in period and tends to remain at this level. At room temperature, such bearings have been operated for up to 10^9 revolutions in high vacuum without any serious degradation in torque behavior. The torque noise will typically be 10 to 15 x 10^{-4} Nm with periods of excessive noise during which peak torque values of up to 200 x 10^{-4} Nm are observed. The torque noise is caused by wear debris from the cage and it is common practice for bearings lubricated in this manner to be flushed with solvent following running-in to remove such debris.

Molybdenum Disulphide

Thin (1 micron) films of MoS_2 were deposited onto the inner and outer raceways of test ball bearings by the technique of magnetron sputtering. This technique leads to the formation of lubricant films which have exceptionally low friction when operated under high vacuum [5], though the actual value of friction coefficient is governed by a number of factors which include contact stress, sliding speed, vacuum pressure, and surface roughness [5,6,7].

The torque behavior and useful lifetime of ball bearings treated with sputtered MoS_2 are dependent on both the cage material and whether the balls as well as the raceways are coated with the lubricant film. It is observed that when only the raceways are lubricated, low torques and relatively short lifetimes are obtained. However, on coating both the balls and the raceways, an improvement in lifetime is gained at the expense of higher torque levels [5]. With regard to cage material, it is observed that bearings fitted with composite PTFE (Duroid) cages exhibit longer lifetimes than bearings fitted with either MoS_2-coated steel cages [5] or cages manufactured from a composite of MoS_2 and polyimide [8].

For the purposes of the present test program, MoS_2-coated bearings were used in conjunction with Duroid cages.

THE ESTL CRYOGENIC FACILITY

The cryogenic test facility consists of a cryostat which is cooled by a Philips PGH 107S Stirling cycle cryogenerator. The cryogenerator is a two-stage expansion engine which circulates helium gas at two quasi-independent stable temperatures - nominally 80 K and 20 K. Because of its attendant noise and vibration, it is installed outside the laboratory in which the cryostat is located. The cold helium gas is circulated between the cryogenerator and the cryostat by means of a vacuum insulated transfer line which contains four pipes - a "supply" and a "return" for each stage.

The cryostat consists of a high vacuum chamber 40 cm in diameter, which contains two thermally isolated copper "cryo-pots" (Fig. 2). These cryo-pots are concentrically mounted, with the inner suspended from the outer by means of three pieces of PTFE. The outer cryo-pot is supported within the vacuum chamber by three stainless steel tubes which are welded to the wall of the vacuum chamber. Heat conduction along these tubes is reduced by including PTFE insulators in the supports. The inner cryo-pot, in which test rigs are housed, has an internal diameter of 250 mm and a depth of 225 mm. Access to the cryo-pots is by way of removable lids on both the vacuum chamber and cryo-pots.

The outer and inner cryo-pots are maintained by the cryogenerator at nominal temperatures of 80 K and 20 K respectively. Thermal contact to the individual cryo-pots is made by "peening" the appropriate supply pipe into the base of the appropriate cryo-pot. The cooling power of the "20 K" stage is 25 W below 19 K; the cooling power of the 80 K cryo-pot has not been measured.

THE EXPERIMENTAL APPARATUS

The Ball Bearing Test Apparatus

The ball bearing test apparatus is shown in position in the vacuum chamber in Figure 2. The apparatus is designed to test a pair of 20 mm bore angular contact bearings arranged in a face-to-face configuration. Details of the bearings are given in Table 1.

The apparatus consists of three main parts: the bearing housing, the drive shaft, and the torque transducer. The housing in which the bearings were located was clamped to the base of the 20 K cryo-pot and cooled conductively (Fig. 2). To minimize differential thermal expansion, both the bearing housing and the bearing mounting (located at the base of the drive shaft) were constructed from low-carbon mild steel. A 38 N preload was applied by means of a stainless steel "deadweight" which rested on the outer raceway of the top bearing. To improve the thermal contact between the preload mass and the cryo-pot, four pieces of copper braid were strapped between the bearing housing and the preload mass. The lower part of the drive shaft was cooled by thermal conduction along the bearing housing and through the bearings themselves.

To aid disassembly, the drive shaft consisted of two sections which were connected by a demountable universal coupling. To minimize thermal conduction down the shaft to the test bearings, the lower (cold) section of the shaft consisted of a glass-fiber-reinforced epoxy rod 6.35 mm in diameter. It was connected at its bottom end to the bearing mounting by means of a second universal coupling. The upper (warm) section consisted of a 6.35 mm diameter stainless steel tube, which was connected at its top end to the torque transducer by a third universal coupling. The shaft was driven by a motor located on top of the vacuum chamber via a ferrofluid rotary feedthrough.

One novel feature of the apparatus was the method used to measure the bearing torque; a torque transducer was mounted integrally with the drive shaft and rotated with the shaft. The transducer was conditioned electrically by means of a slip ring in conjunction with a vacuum feedthrough installed on-axis.

Two types of thermometry were used on the cryostat. The main thermometer was a cryogenic linear temperature sensor (CLTS) [9] which was mounted on the inner cryo-pot. In addition, carbon resistance thermometers were mounted in several locations, as shown in Figure 2. In particular, a carbon resistance thermometer was located at the base of the bearing drive shaft.

EXPERIMENTAL TECHNIQUE

Pairs of angular contact ball bearings were preloaded to 38 N by means of a deadweight, and run at a rotation rate of 100 rpm. The bearing torque and torque noise were measured by a torque transducer, as described above. The output of the torque transducer was recorded on a potentiometric chart recorder and measured by a programmable voltmeter.

Because the drive shaft consisted of two separate shafts which were connected by a demountable coupling, the shaft splayed out radially at rotation rates above 10 rpm and caused an increase in the torque noise. Because of this "run-out" of the drive shaft, all torque measurements described in this paper were made at a rotation rate of 0.44 rpm. It is believed that such measurements, made at reduced speed, are valid, as it is generally observed that the torque of dry-lubricated bearings is independent of rotation rate. During a measurement of torque, the bearings were rotated in both the clockwise and counterclockwise directions for five rotations, while the output of the transducer was sampled at 20 Hz by the voltmeter. Values of the mean and standard deviation of the two signals, as calculated by the voltmeter, were noted for each direction of rotation. The torque signal was also analyzed periodically on a spectrum analyzer to see if it contained a non-dc component. There was no appreciable signal at frequencies above 1 Hz.

A typical torque trace is shown in Figure 3. The mean torque and torque noise are also defined in Figure 3. It should be noted that the range-bars shown on the experimental data represent the total torque variation (that is, six standard deviations) rather than the experimental error; the experimental error is one third of these range-bars. In addition, some of the range-bars include "negative torques." This is due to the elasticity of the (epoxy) drive shaft, and does not originate from the test bearings. In practice, therefore, the range-bars overestimate the actual torque variation.

Each pair of bearings was run in vacuum at room temperature for one million revolutions; the bearing housing was then cooled to below 20 K and the bearings were run for a further two million revolutions. For both the PTFE and the lead, a second pair of bearings was then tested under the low temperature condition only, without an initial "run-in" at room temperature. A similar run for the MoS_2 is in progress.

RESULTS

PTFE (Duroid)

The torque profile of the Duroid-lubricated bearings at room temperature and at 18 K is shown in Figure 4. During the run-in, the mean torque increases from 1.2 x 10^{-3} Nm to a maximum of 3.3 x 10^{-3} Nm. It then decreased progressively to 5 x 10^{-4} Nm, and the bearings were fully run in after approximately 0.5 million rotations. (Note that this torque is exceptionally low for bearings lubricated in this manner, and is below the lowest levels expected from Figure 1.) The torque remained at this level for the remainder of the room temperature measurements. The torque noise after run-in was typically 5 x 10^{-4} Nm. (The torque noise is taken to be $\pm$ 3 standard deviations, hereafter referred to as "3-sigma".) On cooldown (at one million rotations), the torque immediately increased by a factor of approximately three. It remained at this level for the next 1.5 million rotations, at which time the bearings suffered a disturbance which considerably increased both the mean torque and the torque noise. During the final 0.5 million rotations, the mean torque was typically 2.5 x 10^{-3} Nm with a torque noise of 1.7 x 10^{-3} Nm. Both bearings were in very good condition at the end of the run; the raceways were covered with a transfer film, there was no visible pitting, and the cage wear was acceptable. However, on one of the bearings a relatively large piece of Duroid was in the process of being rolled into the running track. It is likely that this caused the disturbance in the torque profile.

The torque profile of Duroid-lubricated bearings operated at 17 K without being run in at room temperature is shown in Figure 5. In a similar manner to the room temperature results, the data contain a maximum which probably corresponds to a low temperature run-in. During this run-in, a larger number of rotations was required to lay down a transfer film, and the mean torque was high and noisy while the film was being transferred - typically 4 x 10^{-3} Nm with a 3-sigma noise of 2.5 x 10^{-3} Nm. However, after the run-in was achieved, the performance was the same as for the bearings which were run in at room temperature. At the end of the run, the condition of both bearings was consistent with that expected for equivalent bearings run in vacuum at room temperature; the raceways were covered with a transfer film, there was no visible pitting, and the cage wear was acceptable.

Lead

The torque profile of the lead-lubricated bearings at room temperature and at 18 K is shown in Figure 6. The torque performance of lead is much noisier than that of Duroid. However, both the mean torque and the torque noise do not change on cooldown, and the torque performance at 18 K remains the same as that at room temperature. At the end of the run, the condition of both bearings was consistent with that expected for equivalent bearings run in vacuum at room temperature; the raceways were covered with a lead/bronze film, there was no visible pitting, and the cage wear was acceptable.

The torque profile of lead-lubricated bearings operated at 17 K without a room temperature run-in is shown in Figure 7. These results are consistent with those described above, and might even indicate that a run-in at room temperature is detrimental since the torque noise observed here is lower. These bearings were also in good condition at the end of the run.

MoS_2/Duroid

The torque profile of the MoS_2/Duroid-lubricated bearings at room temperature and at 17 K is shown in Figure 8. The room temperature behavior was consistent with that expected from Figure 1, the mean torque being typically 4×10^{-4} Nm with a 3-sigma noise of 8×10^{-4} Nm. Immediately after cooldown, the torque was unchanged. However, after 7×10^{4} "cold" rotations the mean torque had increased to 5.6×10^{-3} Nm and the noise had increased to 2.7×10^{-3} Nm. Thereafter, the torque profile was consistent with that obtained for Duroid-lubricated bearings which were not run-in prior to cooldown.

The post-run inspection of the bearings revealed that the MoS_2 film had been removed from the running tracks of both bearings. In addition, a PTFE transfer film had been established, and the condition of the bearings was consistent with that obtained for Duroid-lubricated bearings. It is therefore concluded that the MoS_2 film had poor endurance and ceased to contribute to the lubrication of the bearings after some 7×10^{4} rotations. However, the very first "cold" measurement indicates that the lubricity of MoS_2 is unchanged at 17 K, so it should be possible to use MoS_2 films at cryogenic temperatures, provided that only a few thousand revolutions are required.

DISCUSSION

Duroid

Bearings lubricated by means of a PTFE-based, self-lubricating cage exhibited higher torque and torque noise during operation at cryogenic temperatures. We believe that this behavior can be attributed to the manner in which the shear strength of PTFE increases with decreasing temperature. While the shear strength of PTFE is not known to the authors, it is reported [10] that its value at 200 K is twice that at 300 K. As has been discussed elsewhere [11], the torque is expected to increase proportionately with shear strength. The observed increases in torque are therefore not unexpected.

Lead Film/Lead-Bronze Cage

Our observations on bearings lubricated by lead indicate that their torque behavior is the same as that at 300 K. Furthermore, the evidence indicates that a running-in period at room temperature may not be beneficial to subsequent operation at cryogenic temperatures.

The temperature independence of the torque and torque noise is unexpected, as the shear strength of lead increases by a factor of four on cooling to 20 K [12]. At present we cannot explain these observations, but tentatively propose the following as possible causes:

a) Frictional heat generated in the region of the contact area in which micro-slip occurs is sufficient to increase the local temperature of the lead to a level at which its shear strength is lower than expected.

b) The temperature dependence of the shear strength of thin lead films may differ from that of bulk lead.

c) Adsorption of gas molecules within the vacuum environment gives rise to the formation of surface monolayers whose presence at the interface reduce contact adhesion, thereby reducing friction.

Molybdenum Disulphide/Duroid

The torque behavior may be summarized as follows. On reducing the temperature from 300 K to 20 K, the torque and torque noise are initially unchanged. However, the torque gradually increases, and after approximately 7 x 10^4 revolutions, the torque behavior becomes characteristic of that of bearings lubricated solely by means of a Duroid cage. In addition, our evidence suggests that the MoS_2 film is worn away. We therefore conclude that the endurance of the sputtered MoS_2 films is reduced at a temperature of 20 K.

Our interpretation of this behavior is as follows. At room temperature, a very low torque is developed commensurate with the low friction afforded in vacuum by sputtered MoS_2. At 20 K the torque rises, indicating an increase in friction coefficient. This increase in friction could be due to the adsorption of water vapor which is present in the vacuum system, and indeed comprises the principal gaseous component therein. The effect of the adsorption of very small quantities of water on the lubricity of MoS_2 has been demonstrated previously in vacuum at room temperature [5,6], under which condition a much higher partial pressure of H_2O is required to maintain an adsorbed population. At cryogenic temperatures, water molecules once adsorbed remain adsorbed since their removal by thermal desorption is essentially precluded. In this contaminated state we would expect the friction to be increased and the film endurance to be severely reduced.

A further factor which might contribute to the removal of the MoS_2 film is differential thermal contraction between the steel substrate and the lubricant film. We are unable to calculate the magnitude of any mismatch due to differential contraction because the (average) coefficient of thermal expansivity is not known to us. Nevertheless, such effects will occur to some extent, resulting in stresses in the film which could lead to either the disintegration of the film or its detachment from the surface.

CONCLUSIONS

The following conclusions are drawn with regard to the in-vacuo torque behavior of dry-lubricated bearings:

1. While all the dry-lubricated bearings tested at 20 K survived 2 million revolutions, the best performance was obtained from bearings lubricated with thin lead films and fitted with a lead/bronze cage.

2. Bearings fitted with PTFE-composite cages showed increased torque and torque noise at 20 K. The torque performance of bearings lubricated in this manner was improved by running-in the bearings prior to cooldown.

3. Bearings lubricated with thin lead films and fitted with a lead/bronze cage showed no torque deterioration on reducing the temperature from 300 K to 20 K.

4. Bearings lubricated with sputtered MoS_2 and fitted with Duroid cages showed appreciable increases in torque and torque noise after limited operation at 20 K.

ACKNOWLEDGMENTS

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TABLE 1. DETAILS OF THE TEST BEARINGS.

Race and ball material	AISI 52100 steel (1 percent C, 1 percent CR)
Internal diameter	20 mm
External diameter	42 mm
Width	12 mm
No. of balls	10
Ball diameter	7.14 mm (9/32 in.)
Precision	ABEC 7
Conformity	1.14

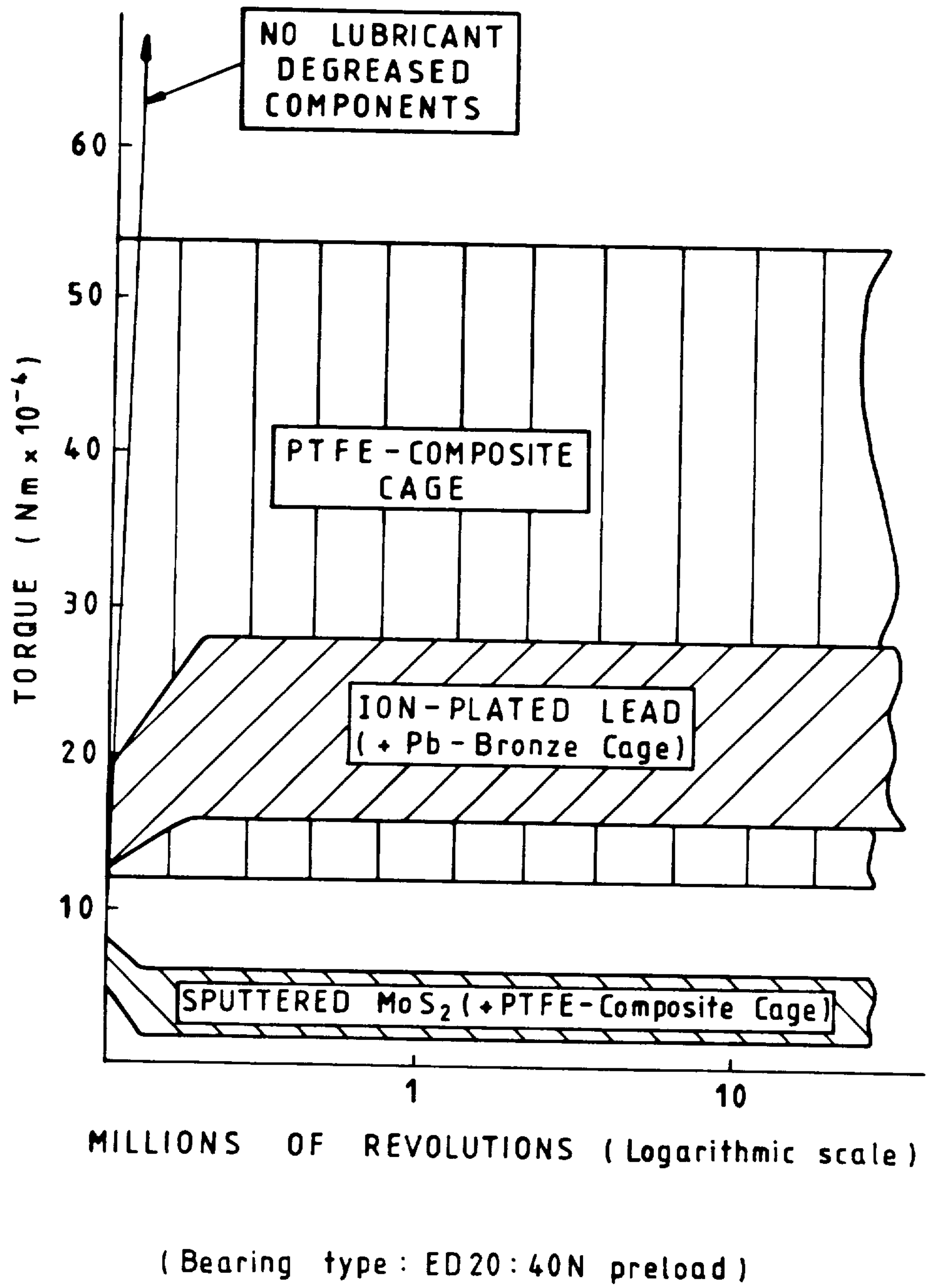

Figure 1. Mean torque bands from repeated tests of solid lubricated ball bearing pairs in vacuum.

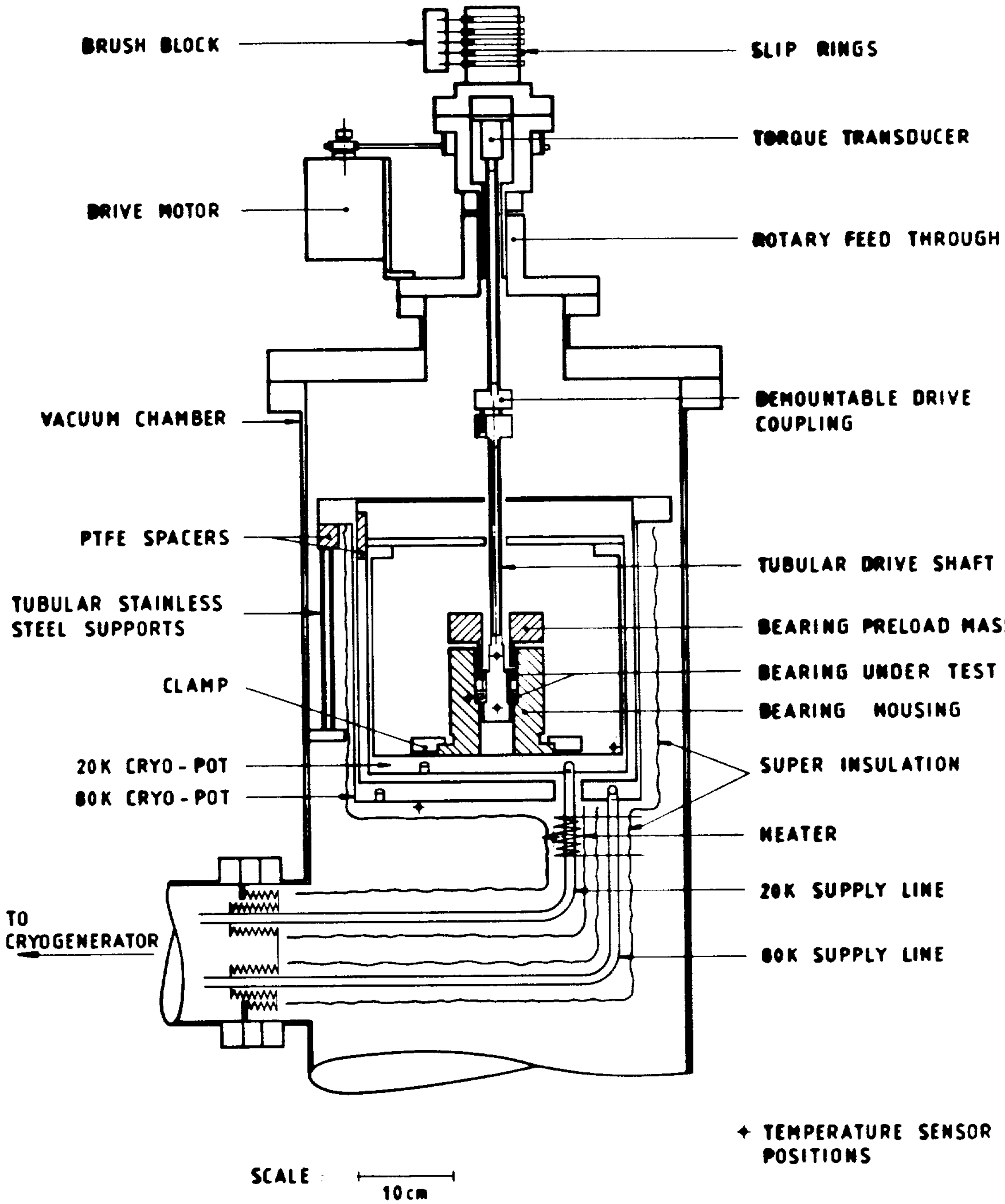

Figure 2. Schematic of the cryogenic vacuum chamber and ball bearing test apparatus.

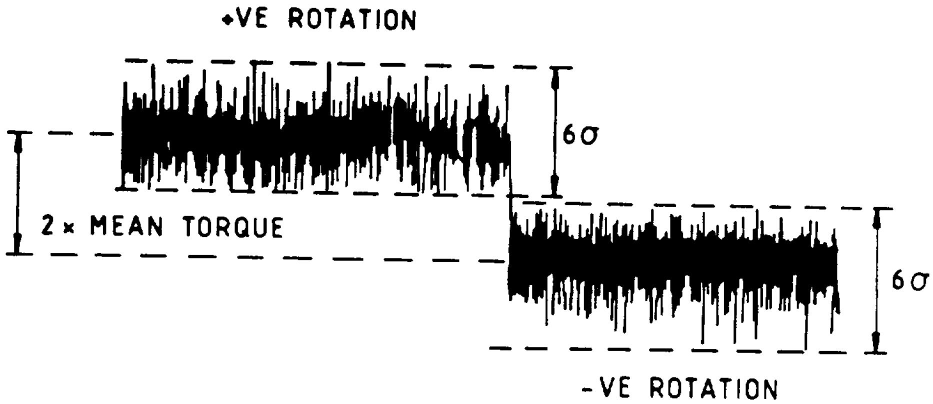

Figure 3. A typical torque trace, showing the definition of mean torque and torque noise (6σ).

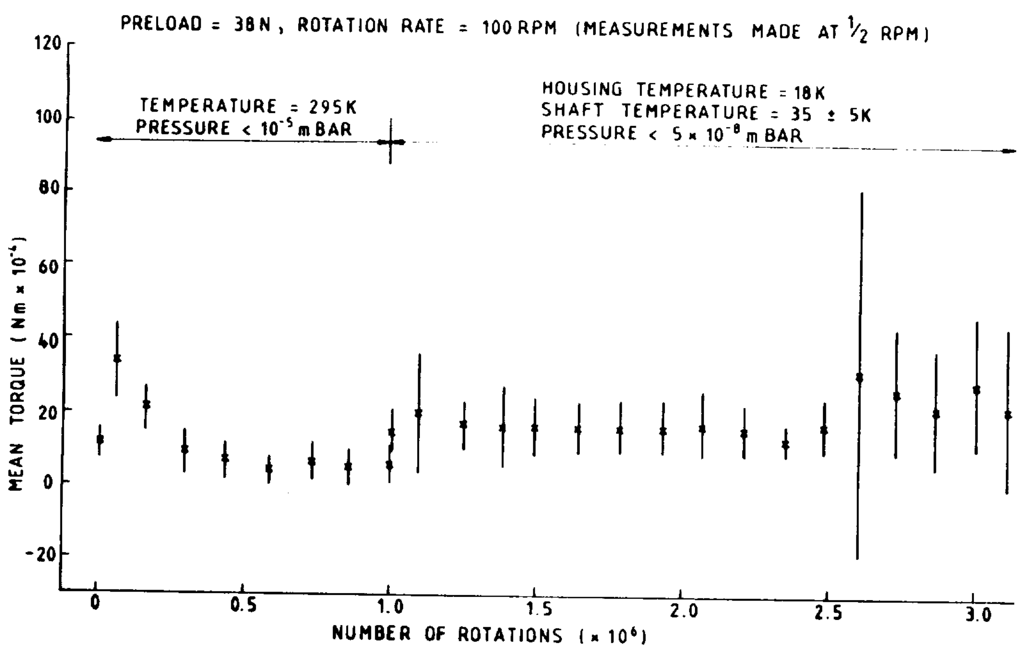

Figure 4. The torque profile of Duroid-lubricated bearings operating at 295 K and at 18 K.

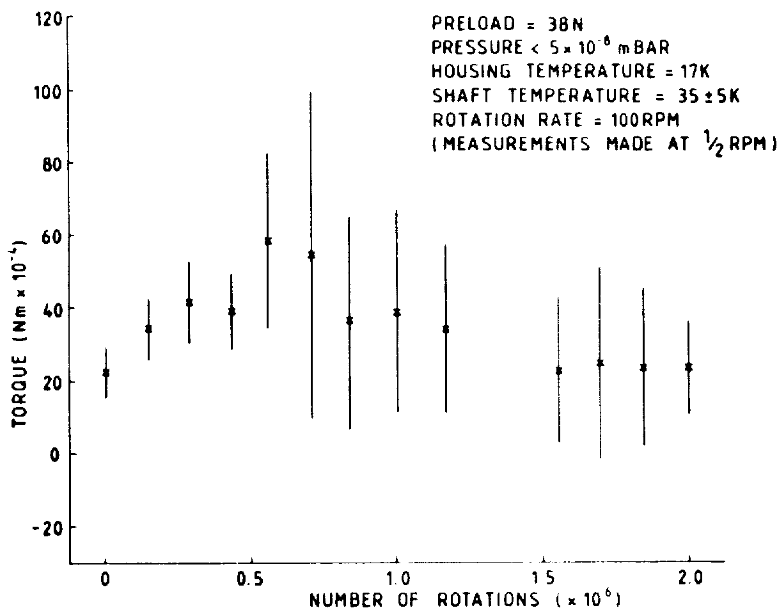

Figure 5. The torque profile of Duroid-lubricated bearings operating at 19 K.

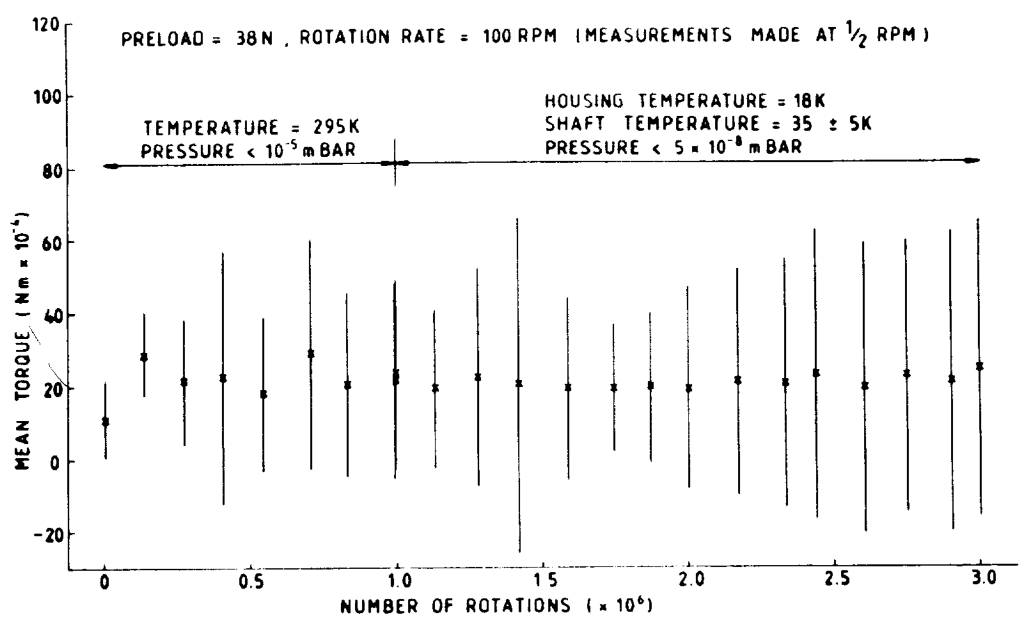

Figure 6. The torque profile of lead-lubricated bearings operating at 295 K and at 18 K.

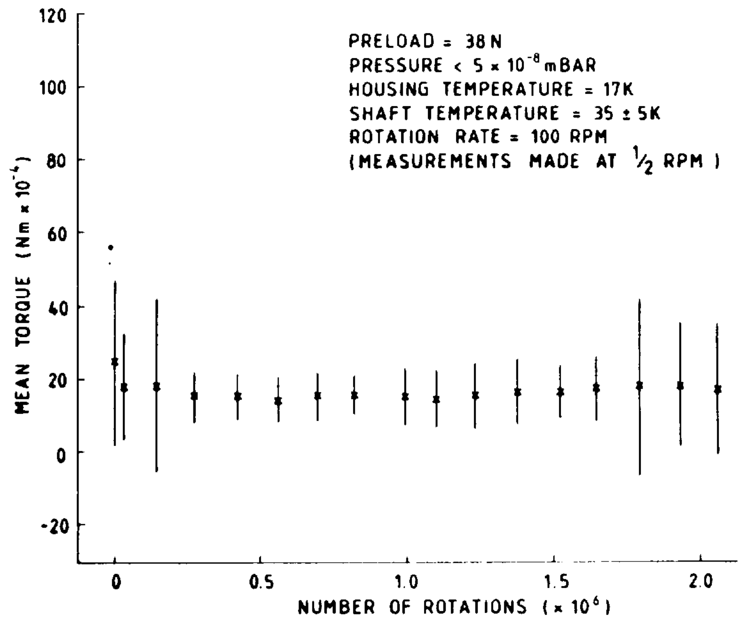

Figure 7. The torque profile of lead-lubricated bearings operating at 17 K.

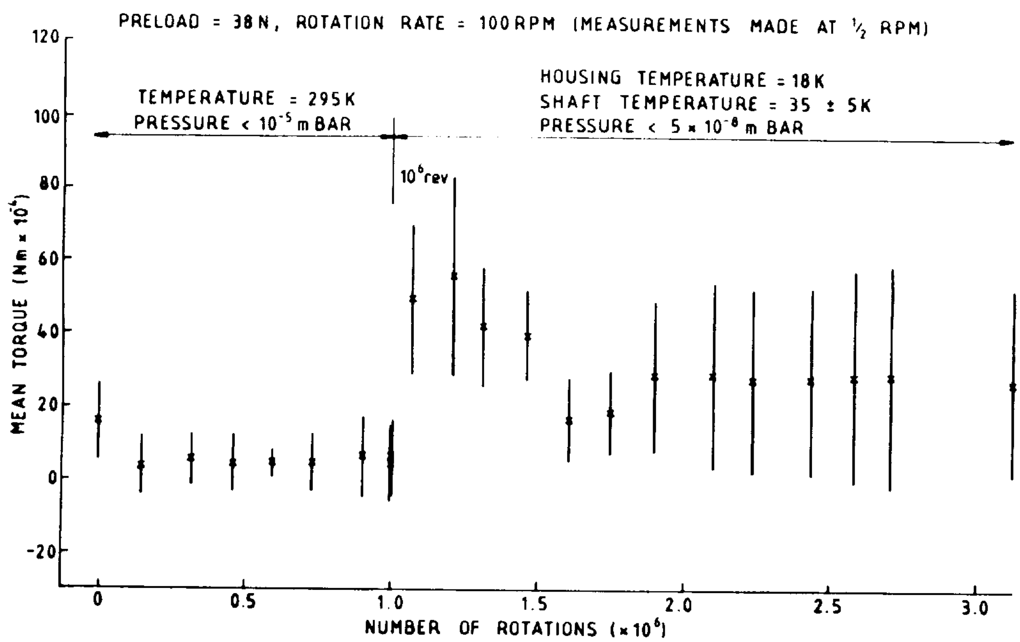

Figure 8. The torque profile of MoS_2/Duroid-lubricated bearings.