

The Preliminary Evaluation of Liquid Lubricants for Space  
Applications by Vacuum Tribometry

W. R. Jones, Jr., S. V. Pepper, P. Herrera-Fierro,  
D. Feuchter, D. T. Jayne, D. R. Wheeler, P. B. Abel,  
E. Kingsbury, W. Morales, R. Jansen, B. Ebihara  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

and

L. S. Helmick  
Cedarville, College  
Cedarville, Ohio

and

M. Masuko  
Tokyo Institute of Technology  
Tokyo, Japan

#### Abstract

Four different vacuum tribometers for the evaluation of liquid lubricants for space applications are described. These range from simple ball-on-flat sliders with maximum in-situ control and surface characterization to an instrument bearing apparatus having no in-situ characterization. Thus, the former provide an abundance of surface chemical information but is not particularly simulative of most triboelements. On the other hand, the instrument bearing apparatus is completely simulative, but only allows post-mortem surface chemical information. Two other devices, a four-ball apparatus and a ball-on-plate tribometer, provide varying degrees of surface chemical information and tribo-simulation. Examples of data from each device are presented.

#### Introduction

The development of new satellite, spacecraft, and space station components will place increased burdens on the tribological systems for the many mechanical moving assemblies (Ref. 1). These assemblies include: momentum/reaction wheels, solar array drives, pointing mechanisms, filter wheels, de-spin mechanisms, slip rings, gears, etc. (Ref. 2). Improved lubrication systems are not only required because of increased mission lifetimes but also to insure greater reliability. In the past,

other components (e.g., batteries, electronics, thermal and optical systems) caused premature spacecraft failure (Ref. 3). It is now apparent, that advances in these areas have now exposed tribology as the primary roadblock in achieving mission requirements.

Liquid lubricants (or greases) are often used in space mechanisms for a variety of reasons. These include: no wear in the elastohydrodynamic (EHL) regime, low mechanical noise, ease of replenishment, relatively insensitive to environment, and ability to scavenge wear debris. A number of different chemical base stocks have been used. These include: mineral oils, esters, polyalphaolefins, perfluoropolyethers (PFPE) and more recently, synthetic hydrocarbons (Ref. 4) and silahydrocarbons (Ref. 5).

Based on the speed, load, temperature, type of motion and type of contact, these lubricants are required to operate in either the EHL, mixed, or boundary lubrication regimes. For a more detailed discussion of these regimes, see Reference 6. Spacecraft designers are in constant need of tribological data for various material/lubricant combinations. These data include: lubricant degradation and outgassing characteristics, friction, torque, and wear characteristics.

Short term characteristics can easily be measured using conventional techniques. However, long term performance of liquid lubricated components poses some difficult problems. Mission lifetimes are typically five to thirty years. This obviously precludes real time testing in most cases. Usually, some form of accelerated test is required. Tests can be accelerated by increasing temperature, load, speed, and duty cycle.

For unlubricated or solid lubricated components, these accelerating methods are usually valid. However, liquid lubricated systems are much more difficult to accelerate. If one is trying to simulate the boundary or mixed film regimes, speed increases may well drive the contact into EHL regime resulting in surface separation. Obviously, this situation is not simulative. In some cases, speed increases are combined with temperature increases. Increasing temperature decreases viscosity and, if carefully controlled, can negate the film forming speed effect. However, high temperatures can initiate chemical reactions and also increase volatility. Stepper motor tests are often accelerated by increasing the duty cycle by removing dead time. This may also cause partial EHL film formation.

#### Vacuum Tribometers

There are four tribometers available at the NASA Lewis Research Center for evaluation of liquid lubricants under vacuum conditions. These are: (1) UHV rubbing apparatus, (2) four-ball apparatus, (3) ball-on-plate apparatus and (4) instrument bearing apparatus.

These devices range from a simple slider with maximum in-situ control and characterization of the flat rubbed surface to a complete rolling contact ball bearing with no in-situ characterization. Since friction and wear is affected by and also alters surface chemistry, in-situ control and characterization are obviously advantageous. However, there are trade-offs in that control and characterization usually require flat geometries that are not simulative of real components. Thus, the greatest degree of control and characterization requires triboelements unrealistically simple and realistic simulation precludes effective in-situ surface analysis. Therefore, our suite of tribometers spans these trade-offs from the simple planar slider with x-ray photoelectron spectroscopy (XPS) providing in-situ analysis but poor simulation to the instrument bearing apparatus providing no in-situ analysis but complete tribo-simulation

### UHV Rubbing Apparatus

The UHV rubbing apparatus is depicted in Figure 1. The device consists of a 6 mm diameter bearing ball which is placed in pure sliding contact with a flat disk. The disk is positioned below the ball and remains stationary during the test. The ball is held in a chuck which is attached to a long rod through a flex pivot assembly. The rod is attached to an XYZ manipulator which is motorized in the Y axis. The entire apparatus is mounted on a 6 inch flange which attaches directly to the preparation chamber of an XPS spectrometer. The virtue of this arrangement is that the flat which is to be rubbed may be subjected to surface analysis and surface treatment (ion bombardment cleaning or in-situ lubricant deposition) without exposure to air either before or after rubbing. Loading is effected by a spring attached to the flex pivot assembly which is extended when the ball contacts the disk surface. Specifications for this tribometer appear in Table 1.

### Four-Ball Apparatus

The overall apparatus is shown in Figure 2. The specimen configuration is the same as the conventional four-ball apparatus, except for the use of 9.5 mm (3/8 in.) diameter precision bearing balls (grade 10). The apparatus is mounted in a vacuum chamber. The chamber is evacuated using a turbomolecular pump (140 l/s) and a mechanical backing pump to achieve a vacuum of approximately  $10^{-4}$  to  $10^{-6}$  Pa. The chamber is equipped with a hot filament ionization gage for chamber pressure and mass spectrometer (residual gas analyzer).

The rotating upper ball is mounted on a spindle which is connected to a ferrofluidic rotary feedthrough. The lower three stationary balls are fixed in a ball holder (lubricant cup) which is mounted on the stage. The stage can be moved upward from outside the chamber with a pneumatic cylinder through a linear motion feedthrough sealed with a welded metallic bellows.

The shaft of the linear motion feedthrough is supported under the "flex pivot" inside the chamber with a linear ball bearing. The lower end of the shaft of the feedthrough is mounted on a plate outside the chamber which is supported with four linear ball bearings. A load cell is mounted between the plate and the pneumatic cylinder to measure the applied load.

The "flex-pivot" shown in Figure 2, which is stiff toward axial thrust but elastic for angular displacement around its center axis is used to mount the stage, where the lubricant cup is fixed, on the top of the shaft of the linear motion feedthrough. Torque is obtained by measuring the angular displacement of the cup holding the three balls. A set of Hall-effect position sensors and a magnet are used to measure the angular displacement. The capability of this tribometer is summarized in Table 1.

### Ball-on-Plate Apparatus

This apparatus is a planar simulation of the rolling contact in a ball bearing. The ball-on-plate geometry is shown schematically in Figure 3. The device consists of a ball set rolling between a stationary bottom plate and a spinning top plate. The apparatus is contained in a turbomolecularly pumped cubical vacuum chamber (typical pressure,  $10^{-6}$ Pa). The top plate is driven by an external motor through a ferrofluidic feedthrough. Load is applied upward on the bottom plate with a deadweight through a lever system located below the apparatus. Typically, for 12.5 mm diameter ball specimens, a total of three balls are used. These are grade 10 precision bearing balls.

These balls are placed between the plates with a positioning device which locates them  $120^\circ$  apart azimuthally and at the same radial distance from the center of the plates. After loading and the start of rotation, the balls will spiral out to the disk periphery. Their spiral path is eventually stopped by a bumper (shown in Figure 3). Each ball in turn is nudged back to its original track once each orbit. This causes a repositioning scrub mark on the bottom plate track, made as the rolling balls are pushed back to their original radius by the bumper. The bumper assembly contains a transducer to determine the force on the bumper. The length of the scrub and the bumper force indicates the degree of boundary lubrication. A cold cathode ionization pressure gauge and a quadrupole mass spectrometer are used to detect species released into the ambient during the rolling and bumping process. The plate to plate electrical resistance determines any separation between ball and plate caused by insulating lubricant films.

The balls are lubricated by a dip coating process by submerging in a dilute solution of the lubricants. Upon removal from this solution, the solvent evaporates, leaving a thin residue of lubricant. The plates are not lubricated but lubricant is transferred during the rolling process. More details about the kinematics of this device appear in Reference 7. Other specifications appear in Table 1.

### Instrument Bearing Apparatus

The final vacuum tribometer is shown in Figure 4. As in the other tribometers, the apparatus is contained in a cubical vacuum chamber and driven by an external motor through a ferrofluidic feedthrough. In this case, the motor is a micro-stepper which is computer controlled to effect either continuous rotation or precise dither motion. Loading is effected by a precision screw mechanism below the apparatus. Provision has been made for either hard or soft loading.

The test component is an instrument angular contact bearing. This bearing has the following specifications: O.D. 30.16 mm, bore 19.05, 18-3.175 mm balls and a porous polyimide retainer. Bearing torque is measured with a flex pivot assembly which is instrumented with micro-strain gages. The vacuum cube is also instrumented with a mass spectrometer. The test bearing is also electrically isolated so that contact resistance can be measured. Other specifications are tabulated in Table 1.

### Examples of Test Data

#### UHV Rubbing Apparatus

This apparatus is generally used to generate tribological surfaces for fundamental surface chemistry studies. Typically a flat surface is cleaned and characterized by X-ray photoelectron spectroscopy (XPS). Then it is placed on a collimator and a thin (~40 Å) lubricant film is deposited by evaporation. An in-situ rubbing experiment can then take place. An example is shown in Figure 5 from Reference 8.

Figure 5 is a micrograph of a rubbed area on a 440 C disk lubricated with a perfluoropolyether (PFPE). The area was generated by loading a 440 C bearing ball against the flat translating it linearly in reciprocating motion with a velocity of 0.3 mm/s. A lateral translation of 50 µm at the end of each stroke produced a rectangular patch 5 mm X 8 mm. XPS analysis of this rubbed area indicated that, even under this mild sliding, single pass conditions, surface fluoride was formed. This indicated that the PFPE had been degraded at room temperature. Its chemical signature was similar to that observed during static high temperature experiments. Therefore, this device is very useful in studying the effects of surface pretreatments, such as ion implantation, on the tribological process.

#### Four-Ball Apparatus

Because of the high loads and pure sliding conditions employed in this device, a great amount of energy is dissipated in the contact regions. This accentuates chemical reactions and therefore results in a highly accelerated test. Steady state wear rates are generated with this device which yield qualitative rankings of the boundary lubrication performance of liquid lubricant basestocks and formulations.

Figure 6 contains a comparison of wear rates for three aerospace lubricants in air and vacuum (Ref. 9). Test conditions were: 25°C, 200N load, and a 100 rpm rotational speed. The three lubricants were (1) an unbranched PFPE (Z-25), (2) a branched PFPE (143 AB) and (3) a formulated synthetic hydrocarbon (2001). Results in air and vacuum clearly discriminate between the more reactive unbranched PFPE (Z-25) compared to the less reactive branched fluid (143 AB). This trend correlated with other vacuum four-ball results (Ref. 10) and vacuum sliding experiments (Ref. 11). In addition, the better performance of formulated hydrocarbons compared to unformulated PFPE fluids correlated with oscillating gimbal tests (ref. 12) and boundary lubricant screening tests (ref. 13).

#### Ball-on-Plate Apparatus

Figure 7a shows bumper force and mass spectrometer data obtained with a PFPE boundary lubricant at room temperature, 6 rpm and  $10^{-6}$ Pa. In this test the bumper force reached a maximum of 28N and lasted 1.2 seconds. The ball load was 140N, for a sliding friction coefficient of 0.2. Figure 7b shows the corresponding mass spectrometer data for evolution of mass 69 ( $CF_3$ ) lubricant fragments: background, no rotation, level I; rotation, no bump, level II; and during a series of bumps, level III.

#### Instrument Bearing Apparatus

Performance data for an MPB 1219 size bearing operating in a retainerless mode and lubricated with a synthetic hydrocarbon (Nye 2001) are shown in Figure 8. Figure 8 illustrates the effect of speed on torque and contact resistance at room temperature, a hard load of 44.5 N and a vacuum level of approximately  $10^{-4}$ Pa. A gradual increase in torque with increasing speed is observed. Contact resistance as a function of speed shows the transition from the boundary regime to mixed and finally to full EHL.

#### References

1. Fusaro, R.L.: "Tribology Needs for Future Space and Aeronautics Systems," NASA TM-10425, 1991.
2. Fusaro, R.L. and Khonsari, M.M.: "Liquid Lubrication for Space Applications," NASA TM-105198, 1992.
3. Fleischauer, P.D. and Hilton, M.R.: "Assessment of the Tribological Requirements of Advanced Spacecraft Mechanisms," Aerospace Corporation, Report No. TOF-0090 (5064)-1, Sept. 1991.
4. Vernier, C.G.: "Multiply-Alkylated Cyclopentanes (MACS): A New Class of Synthesized Hydrocarbon Fluids," Lubr. Engr. 47, 7, pp. 586-591, July 1991.

5. Tamborski, C.; Chen, G.J.; Anderson, D.R.; and Snyder, C.E., Jr.: "Synthesis and Properties of Silahydrocarbons, A Class of Thermally Stable, Wide-Liquid-Range Fluids," *Ind. Eng. Chem. Prod. Res. Deve.* 22, p. 172, 1983.
6. Jones, W.R., Jr.: "The Properties of Perfluoropolyethers Used for Space Applications," NASA TM-106275, 1993.
7. Kingsbury, E.: "Kinematics of an Elastic Sphere Rolling on a Plane and Between Two Planes," *Trans. ASME* 115, pp. 476-480, July, 1993.
8. Herrera-Fierro, P.; Jones, W.R., Jr.; and Pepper, S.V.: "Interfacial Chemistry of a Perfluoropolyether Lubricant Studied by XPS and TDS," NASA TM-105840, 1992.
9. Masuko, M.; Jansen R.; Ebihara, B.; and Pepper, S.V.: "A Vacuum Four-Ball Tribometer to Evaluate Liquid Lubricatns for Space Applications," NASA TM-106264, 1993.
10. Masuko, M.; Fujinami, I.; and Okabe, H.: "Lubrication Performance of Perfluoropolyalkylethers Under High Vacuum," *Wear*, 159, pp. 249-256, 1992.
11. Mori, S. and Morales, W.: "Tribological Reactions of Perfluoroalkyl Polyether Oils with Stainless Steel under Ultrahigh Vacuum Conditions at Room Temperature," *Wear*, 132, pp. 11-121, 1989.
12. Conley, P.L. and Bohner, J. J.: "Experience with Synthetic Fluorinated Fluid Lubricants," Twenty-fourth Aerospace Mechanism Symposium, NASA CP-3062, pp. 213-230, Apr. 18-20, 1990.
13. Hilton, M.R. and Fleischauer, P.D.: "Lubricants for High-vacuum Applications,": Aerospace Report No. TR-0091 (6945-03)-6, Mar. 1993.

Table 1. Specifications of Vacuum Tribometers

Apparatus	UHV Rubbing	Four-Ball	Ball-on-Plate	Instrument Bearing
Initial Mean Hertz Stress, GPa	0.43	2-4	1-2	1-1.5
Motion	pure sliding/ reciprocating	pure sliding	rolling/ sliding/ pivoting	rolling/ sliding/ dither
Atmosphere	air, N <sub>2</sub> , or vacuum	air, N <sub>2</sub> , or vacuum	air, N <sub>2</sub> , or vacuum	air, N <sub>2</sub> , or vacuum
Load Range, N	~1N	50-1000	45-450	25-200
Speed Range, rpm	0.02-0.2 (linear speed)	10-500	1-100	1-1200 (1Hz dither)
Environmental Pressure, Pa Temperature	10 <sup>-7</sup> room	10 <sup>-6</sup> room to 50°C	10 <sup>-6</sup> room to 50°C	10 <sup>-6</sup> room to 50°C
Specimens (440C Steel)	6 mm diameter bearing ball	9.5 mm diameter bearing balls	12.7 mm diameter bearing balls 50.8 mm diameter disks	angular contact instrument bearing (1219 size)

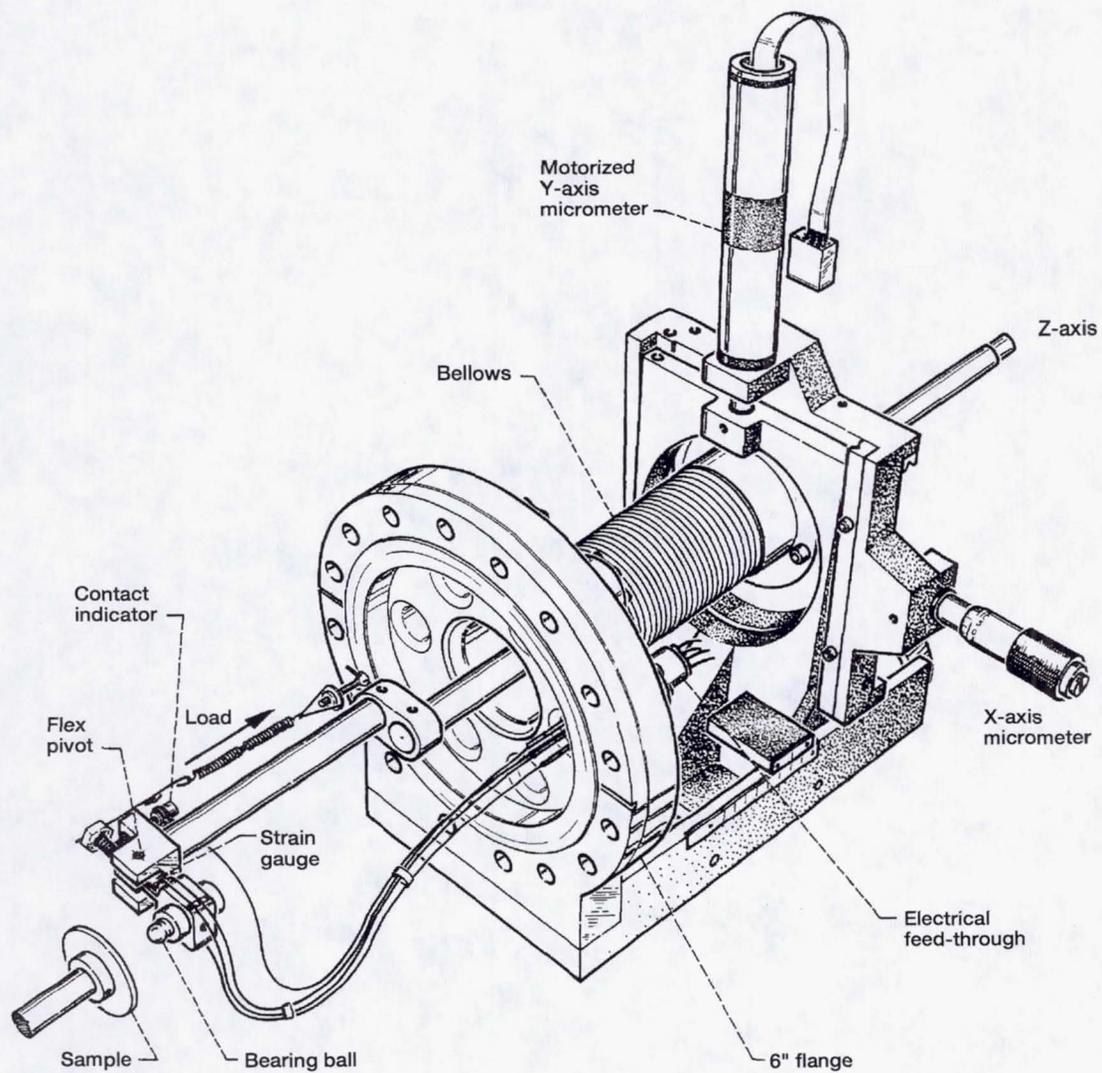


Figure 1.—UHV tribometer.

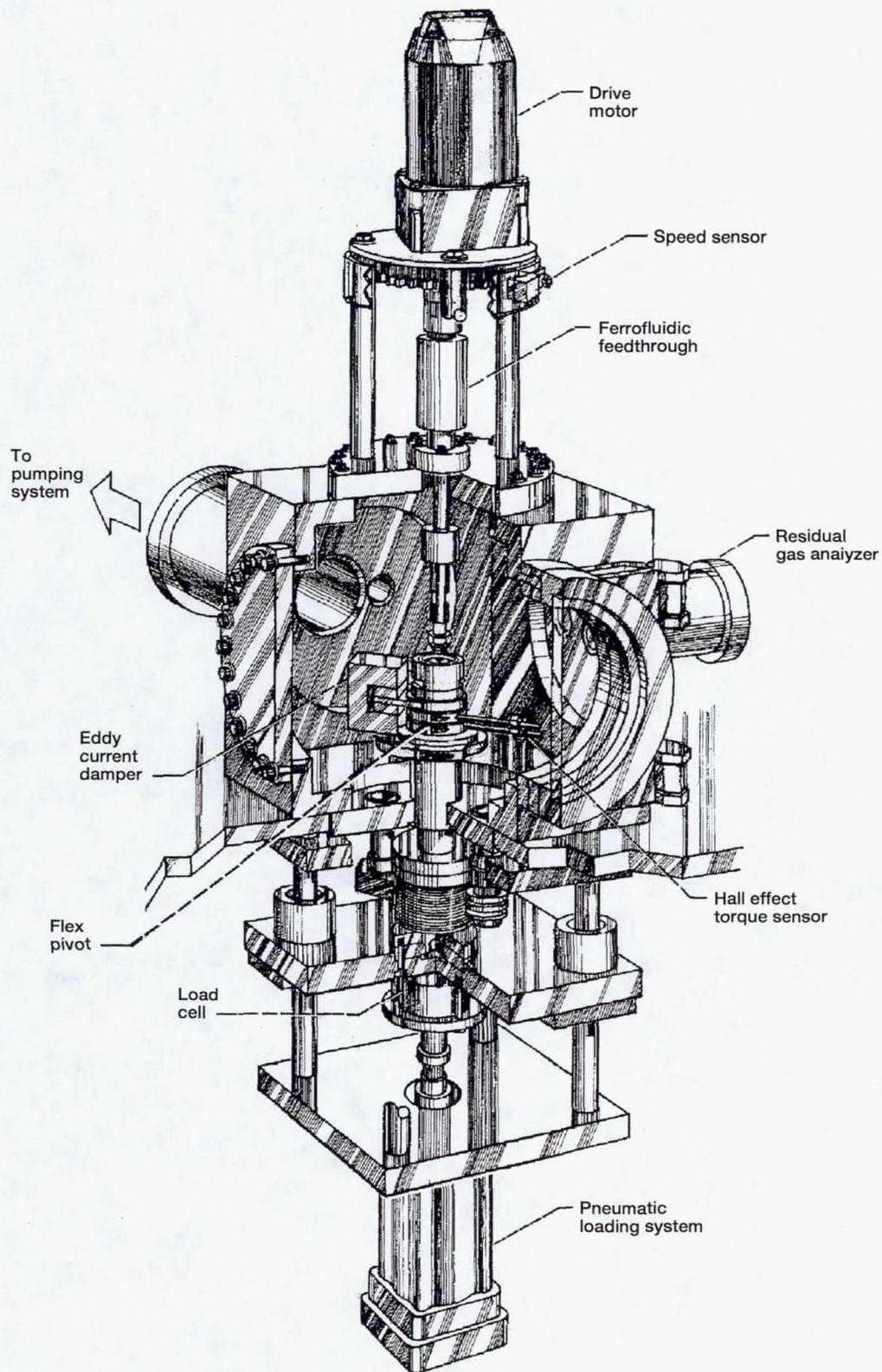


Figure 2.—Four-ball apparatus.

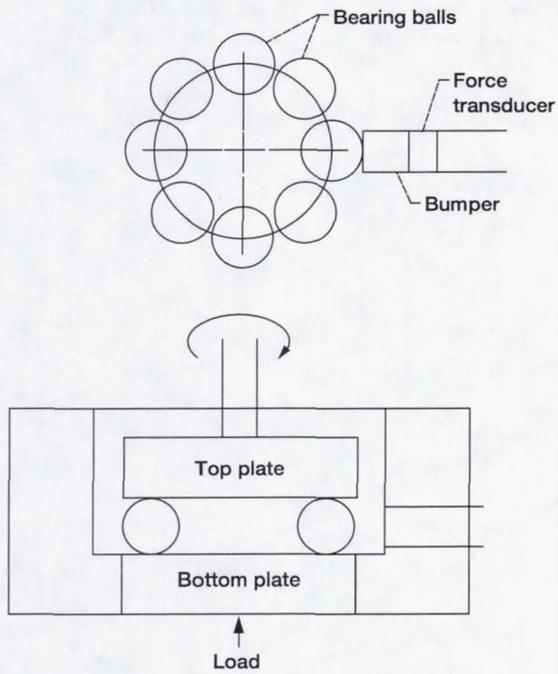


Figure 3.—Ball-on-plate geometry.

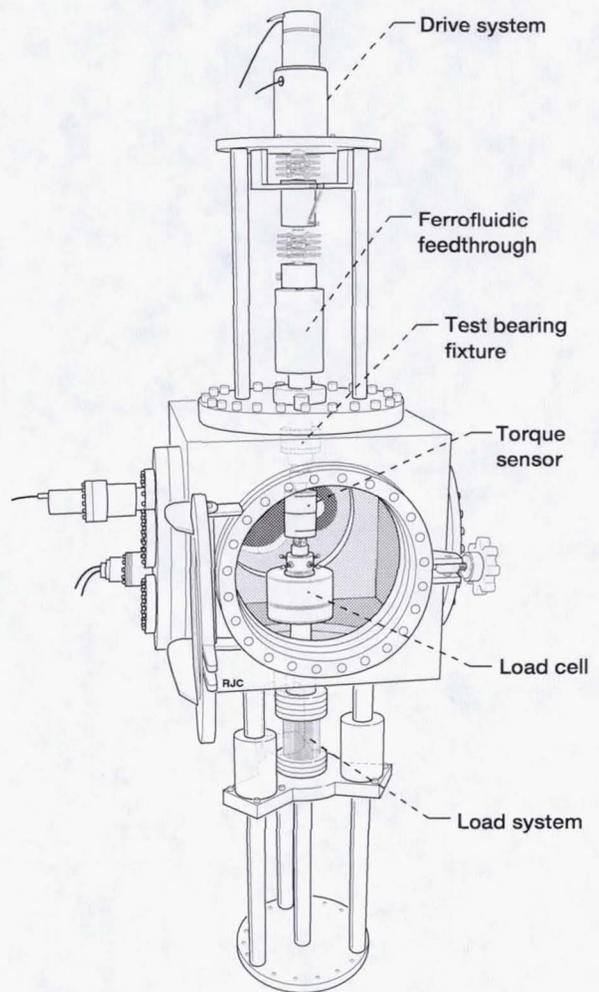


Figure 4.—Instrument bearing test rig.



Figure 5.—Optical micrograph of soft 440C steel surface after rubbing with a 440C bearing ball. Lubricant: 50Å Fomblin Z-25.

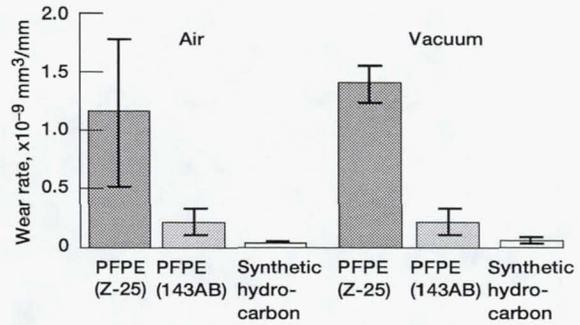


Figure 6.—Wear rates for three commercial aerospace lubricants in air and vacuum (25 °C, 200N load, 100 RPM).

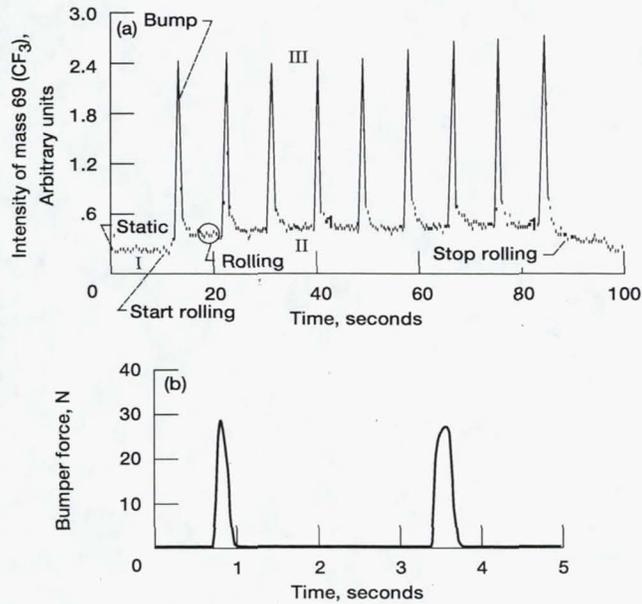


Figure 7.—(a) Intensity of mass 69 (CF<sub>3</sub>) from residual gas analyser as a function of time. (b) Bumper force as a function of time (lubricant, Krytox 16256; load, 140N; vacuum, 10<sup>-6</sup>Pa; speed, 6 RPM).

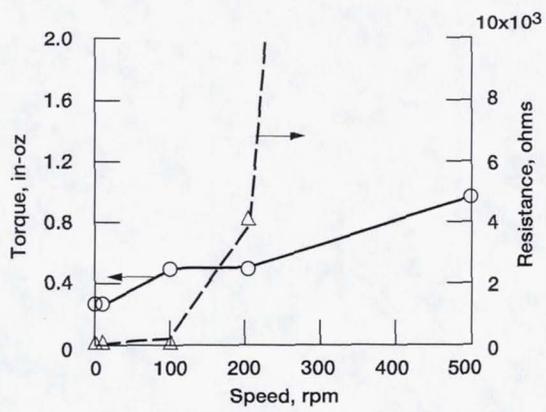


Figure 8.—Bearing torque and contact resistance as a function of speed (44.5N hard load).