Designation: F2661 − 07 (Reapproved 2015)

Standard Test Method for Determining the Tribological Behavior and the Relative Lifetime of a Fluid Lubricant using the Spiral Orbit Tribometer[1]

This standard is issued under the fixed designation F2661; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the quantitative determination of the friction coefficient and the lifetime of oils and greases, when tested on a standard specimen under specified conditions of preparation, speed, Hertzian stress, materials, temperature, and atmosphere, by means of the Spiral Orbit Tribometer (SOT). This test method is intended primarily as an evaluation of the lifetimes of fluid lubricants under vacuum and ambient conditions.

1.2 This standard may involve hazardous materials, operations, and equipment. *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1193 Specification for Reagent Water

F22 Test Method for Hydrophobic Surface Films by the Water-Break Test

F2215 Specification for Balls, Bearings, Ferrous and Nonferrous for Use in Bearings, Valves, and Bearing Applications

G115 Guide for Measuring and Reporting Friction Coefficients

2.2 *Anti Friction Bearing Manufacturers Association Standards*[3]

ANSI ABMA ISO 3290 (AFBMA Standard 10 Balls)

3. Terminology

3.1 *Definitions:*

3.1.1 *coefficient of friction*—the dimensionless ratio of the friction force between two bodies to the normal force pressing these bodies together.

3.1.2 *fixed plate*—stationary, horizontal flat plate, typically through which a force (the "load") is applied to the ball.

3.1.3 *friction coefficient limit*—maximum value that the friction coefficient is permitted to attain.

3.1.4 *guide plate*—physical element that deflects the ball to its original orbit radius.

3.1.5 *lubricant total amount*— mass of lubricant deposited on the entire ball surface at the beginning of the test.

3.1.6 *normalized lifetime*—number of ball orbits performed until the friction coefficient limit is reached divided by the lubricant total amount initially deposited on the ball.

3.1.7 *rotary plate*—flat plate rotating at a constant rate selected for the test.

3.1.8 *scrub zone*—Region of the ball's orbit in which the ball is in contact with the guide plate.

3.1.9 *spiral orbit*—track traced by the ball on the fixed and rotating plates of the Spiral Orbit Tribometer. The track has a spiral shape.

4. Summary of Test Method

4.1 A lubricated ball is clamped between two parallel plates. One of the plates rotates up to 210 rpm, causing the ball to roll in a near-circular orbit, but is actually an opening spiral. A clamping force, the "load", provides a chosen mean Hertz stress (typically 1.5 GPa). The system is targeted to operate in the boundary lubrication regime due to the combination of the high load, the moderate speed, and the small amount of lubricant (approximately 50 µg). The ball rolls and pivots in a spiral orbit and is maintained in the orbit by the guide plate. The ball slides on the rotating plate when it contacts the guide plate. The measured force exerted by the ball on the guide plate is used to determine the friction coefficient. The tribometer runs until the coefficient of friction rises to values much larger than the initial, steady value. At this point the initial charge of

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[1] This test method is under the jurisdiction of ASTM Committee F34 on Rolling Element Bearings and is the direct responsibility of Subcommittee F34.02 on Tribology.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American Bearing Manufacturers Association (ABMA), 8221 Old Courthouse Road, Suite 207 Vienna, Virginia 22182.

lubricant has been depleted by tribodegradation and the system is running virtually unlubricated. The normalized lifetime is obtained from the number of spiral orbits completed before reaching the chosen friction coefficient limit divided by the total lubricant mass on the ball at the beginning of the test. A minimum of four tests per lubricant and test condition shall be performed. Lubricants can be compared by calculating their average normalized lifetimes for a given set of test conditions.

5. Significance and Use

5.1 *Relevance of the Spiral Orbit Tribometer (SOT)*—The SOT was designed to evaluate the relative degradation rates of liquid lubricants in a contact environment similar to that in an angular contact bearing operating in the boundary lubrication regime. It functions as a screening device to quickly select the lubricants, evaluate the ability of various components of a lubricant (base oil, thickener, or additive) to lubricate a contact in rolling, pivoting, and sliding conditions simultaneously, and study their chemical decomposition if necessary. The SOT provides a means to study the tribological behavior of oils and greases during operation, while they undergo changes as a function of typical parameters encountered in the lubrication field (temperature, environment, materials used, load applied, and speed). Test conclusion is defined to be when a friction coefficient limit (typically an increase of 0.1 above the steady state value) is surpassed. Normalized lubricant lifetime is then defined as the number of orbits completed divided by the initial amount of lubricant used (in µg). The SOT was initially developed to evaluate lubricants for space applications, but is also relevant for conventional environments. Some results in vacuum are presented (Fig. 1). At this time, no data for tests in ambient conditions have been published (see Fig. 2). The user of this test method should determine to their own satisfaction whether results of this test procedure correlate with field performance or other bench test procedures.

6. Apparatus

6.1 *The Spiral Orbit Tribometer (SOT)*—See Fig. 3.

6.1.1 *General description*—Fig. 3 shows a schematic drawing of a typical SOT. The system consists of a lubricated ball rolling and pivoting between a fixed plate and a rotary plate. The load is applied through the fixed plate. The track is a spiral and the ball is returned to its original orbit radius by contacting the guide plate, which forces the ball to return to its original radius each orbit. The friction coefficient is determined by the measuring the force on the guide plate when the ball contacts the guide plate. A piezoelectric force transducer is attached to the guide plate. This force, divided by twice the normal load, is the friction coefficient.

6.1.2 *Motor drive*— A variable speed motor, capable of constant speed, is required. Rotating plate speeds are typically in the range 1 to 210 rpm (0.10 to 22 rad.s $^{-1}$). The effective stiffness of the axis shall be at least 1.8 E +05 Newton/meter axial in the load direction, 3.6 E +08 Newton/meter radial and 1.13 E +05 Newton-meter/Radian moment. The TIR of the motor shaft shall be 0.0254 millimeters maximum.

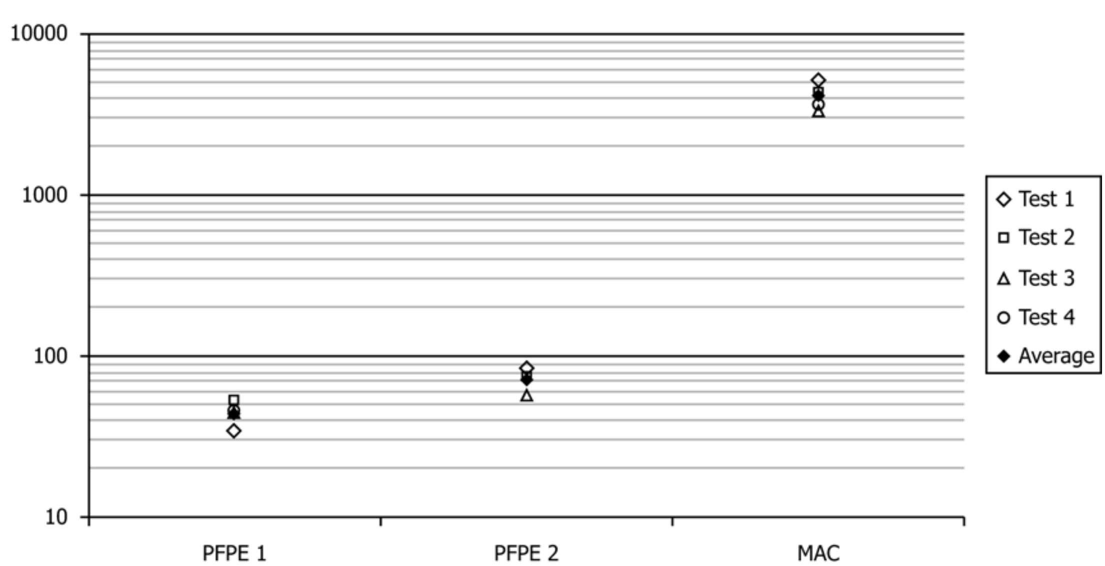
6.1.3 *Fixed load plate*— The load plate shall have an axial stiffness of at least 1.8 E +08 Newton/meter in the load direction. The effective radial stiffness of the plate axis shall be at least1.8 E+08 Newton/meter and the moment stiffness shall be at least 1.13 E +05 Newton-meter/Radian.

6.1.4 *Orbit counter*— The SOT shall be equipped with a revolution counter or its equivalent that will record the number of ball orbits. The tribometer would preferably have the ability to shut off after a pre-selected number of orbits or friction coefficient has been reached.

6.1.5 *Applied load*— The fixed plate is attached to a system to apply the load, up to 222.5 N (50 lb.), providing the desired Hertzian stress, typically 1.5 GPa.

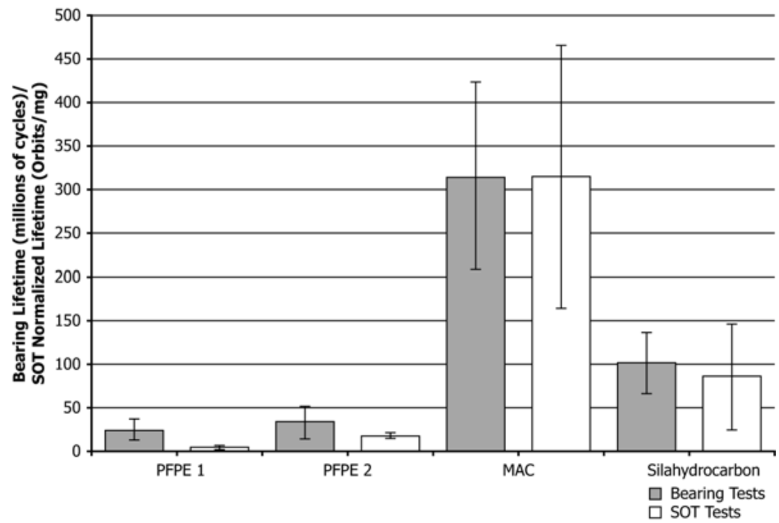
6.1.6 *The instruments and gauges:*

6.1.6.1 *Friction force*— The friction coefficient is determined by measuring the force on the guide plate while the ball contacts the guide plate. This force is measured using a piezoelectric force transducer and a charge amplifier. The friction force and the coefficient of friction can then be



Pepper, S.V., Kingsbury, E.P., "Spiral Orbit Tribometry – Part II: Evaluation of Three Liquid Lubricants in Vacuum", *Tribo. Trans.*, V 46, 1, pp 65-69, 2003

FIG. 1 Relative lifetimes of three typical space lubricants at 23°C in vacuum on 52100 steel



Bazinet, D.G., Espinosa, M.A., Loewenthal, S.H., Gschwender, L., Jones, W.R., Jr., Predmore, R.E., "Life of Scanner Bearings with Four Space Liquid Lubricants", *Proc. 37th Aerospace Mech. Symp.*, Johnson Space Center, May 19-21, 2004

FIG. 2 Comparison between full scale bearing tests and SOT data at 23°C on 440C steel.**

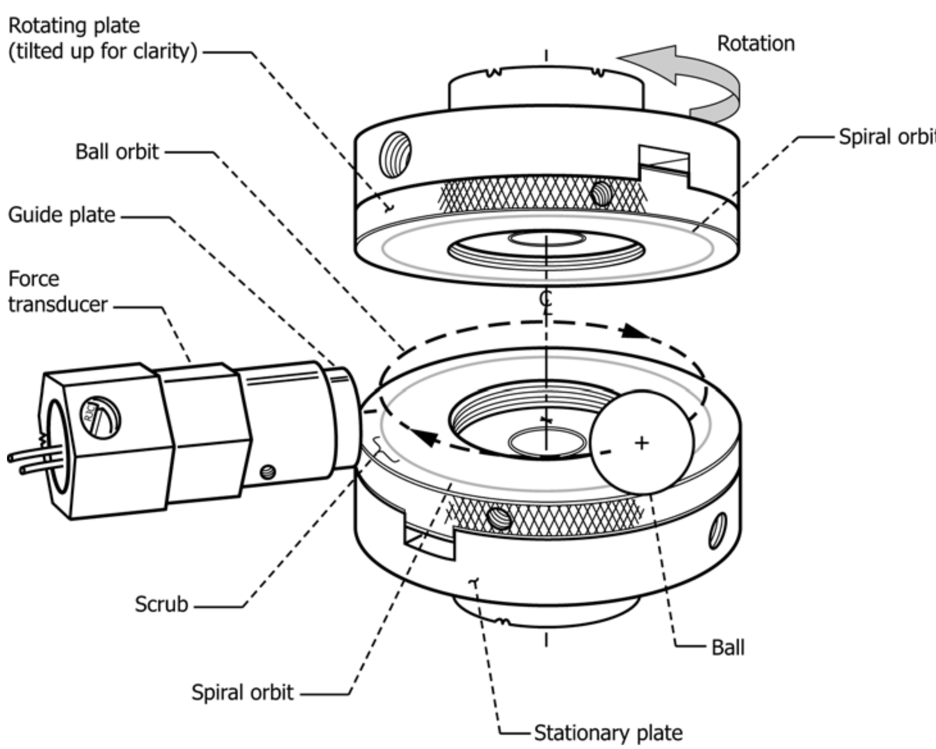


FIG. 3 Detail of the Spiral Orbit Tribometer

obtained as explained in Section 11. The load cell shall be linear to within 2 % across the entire temperature range of the test.

6.1.6.2 *Environment*— The SOT operates in either one atmosphere air, under a cover gas, or vacuum. When operating under vacuum or ultrahigh vacuum, a cold cathode pressure gauge attached to the chamber monitors the pressure. A hot cathode gauge should be avoided since electrons from the filament could alter lubricant chemistry. It is the responsibility of the user to determine the chemical purity of the environment and gas to establish the contribution to tribochemistry.

6.1.6.3 *Measurement of the temperature* —When a controlled temperature is required, the temperature is monitored using a thermocouple (for example, K-type) attached to the stationary disk during the test.

7. Reagents and Materials

7.1 Balls, plates, guide plates. Typical instrument bearing materials may be of 440C material, but other materials may be used to simulate the bearing application.

7.1.1 *Test balls*—Test balls shall be 12.7 mm (0.5 inch) diameter, grade 25 or better, made with 440C stainless steel.

Their recommended Rockwell hardness shall be 58 to 62. See Specification F2215 or ANSI ABMA ISO 3290 (AFBMA Standard 10) for ball specification reference. Other materials may be used to simulate specific application chemistry.

7.1.2 *Plates, Guide plates*—The fixed plate and the rotary plate are disks of 50.8 mm (2 inch) in diameter, may be made with 440C stainless steel, or any desired material. Surface roughness of 0.05 mm average roughness or less is recommended. The guide plates are small cylinders 12.7 mm (0.5 inch in diameter), with a polished surface of 0.05 mm average roughness or less (recommended). The recommended Rockwell hardness for 440C shall be 58 to 62. Stationary and rotary plates should be made with the same material. Any bearing material can be used, depending on the application being simulated. The recommended values should be used unless differences are required to simulate a specific application.

7.1.3 Care must be taken in surface preparation and handling to avoid surface damage or contamination after cleaning that alters the material. Typical cleaning methods may be used when the results will pass an Test Method F22 standard test for wetability and do not damage the materials or adversely alter the sample surfaces. A wettability test using the intended lubricant to evaluate the ball and plate cleaning method is recommended.

7.1.4 Reagent grade chemicals shall be used per Test Method F22 section 8.1. It is the user's responsibility to prevent contamination or adulteration of the lubricant samples, and prevent materials used to clean or lubricate from harming the samples.

8. Hazards

8.1 *Use of solvents*— Operator will refer to the safety data sheet of all the solvents used and will take appropriate precautions.

8.2 *Use of ultrasonic cleaning systems (if applicable)*—Operator will refer to the instruction manual of the ultrasonic bath before use.

8.3 *Use of ultra violet (U.V.)/ozone cleaning system (if applicable)*—Operator will refer to the instruction manual of the U.V./ozone cleaning system before use. Special care will be taken to check the compatibility of the materials used to a U.V. and ozone exposure.

8.4 *Ultrahigh vacuum chamber (if applicable)*—The vacuum chamber will be operated with appropriate copper or elastomer seals to reach ultrahigh vacuum, and will not be opened until the inside of the chamber has reached atmospheric pressure.

9. Sampling, Test Specimens, and Test Units

9.1 *Test specimens*— Specimens (plates, balls, guide plates) will be kept for further analysis, if required.

9.2 *Test units*—Only SI units will be used.

10. Procedure

10.1 Cleaning of the parts and tools may be any method that simulates the application. It is recommended that the results of cleaning procedures are tested using a water break free test such as Test Method F22 using reagent grade water per Specification D1193, or a wettability test using the intended oil. Since many variations of cleaning methods exist and their results may have a strong effect on the results, it is the user's responsibility to determine the effectiveness and safety of the cleaning methods. The details of the cleaning methods shall described in the test report.

10.2 *Lubrication of the balls*—Lubrication of the test system is to the ball only. The objective is to lubricate the balls with a small and controlled amount of lubricant. The target amount is as close as possible to 50 +/− 2 µg for a 12.7 mm diameter ball.

10.2.1 *Lubrication of the balls with oil:*

10.2.1.1 Preparation of a dilute solution of oil:

(1) Choose a solvent suitable for the oil to be tested. The user must determine that the solvent does not harm the sample surface or alter the lubricant.

(2) Weigh a clean, dry and empty bottle.

(3) Put a small drop of oil within the bottle.

(4) Note the mass of oil (m_{oil}) in milligrams.

(5) Add a volume of solvent in the bottle to obtain the proportion of one milliliter of solvent per one milligram of oil.

(6) Close the bottle and shake it to create an homogeneous solution.

It is the responsibility of the user to determine the type of solvent used. Some solvents may not produce a homogeneous solution and can have an adverse effect on the results. Care must be taken to produce a final lubricant film that is unadulterated on the ball.

10.2.1.2 *Lubrication of the ball:*

(1) Weigh a dry, clean ball with a micro-balance to ±2 µg.

(2) Fill a micro-syringe with the dilute oil solution.

(3) Attach the ball to a handling tool that spins the ball and start the ball spinning.

(4) Put fifty microliters, drop by drop, of the dilute solution on the surface of the spinning ball.

(5) Wait at least five minutes or until the weight of the sample is stable to allow the solvent to evaporate.

(6) Remove the ball from the spinning device.

(7) Weigh the lubricated ball with a micro-balance to ±2 µg.

(8) Determine the amount of oil, in µg, on the ball and record.This procedure has to be done for the minimum four balls used to test the oil sample. To avoid contamination, it is recommended that each ball be lubricated just prior the start of each test.

10.2.2 *Lubrication of the balls with grease:*

10.2.2.1 Preparation of the material:

(1) Cut six 5 cm^2 squares in a polyethylene sheet.

(2) Attach each square on the top of a beaker with a rubber band.

(3) Make sure the polyethylene squares are forming an elastic membrane.

(4) Clean each square surface with a clean room wipe and IPA, followed with a flush of clean IPA

(5) Dry each square surface with clean dry air or nitrogen and take precautions to prevent a buildup of a static charge and the attraction of particulate or lint.

10.2.2.2 Lubrication of the ball:

(1) Weigh a dry, clean ball with a microbalance to ±2 µg.

(2) Put a very small amount of grease on the ball (less then 1 mm^3).

(3) Place the ball between two polyethylene squares fixed to the beakers.

(4) Roll the ball for one minute between the two polyethylene squares.

(5) Place the ball between the second set of two polyethylene squares fixed to the beakers.

(6) Roll the ball for 30 seconds on the two polyethylene squares.

(7) Place the ball between the third set of polyethylene squares fixed to the beakers.

(8) Roll the ball for 15 seconds between the two polyethylene squares.

(9) Weigh the lubricated ball with a microbalance to ±2 µg.

(10) Determine the amount of grease, in µg, on the ball.

The consistency varies from grease to grease. In some cases, the amount of grease is too much or too little. The operator will again need to roll the ball between one or all the sets of polyethylene squares until the appropriate amount of grease is reached. The goal is to apply as near to 50 µg as possible.

This procedure has to be done for the minimum of four balls used to test the grease sample. To avoid contamination, it is recommended that each ball be lubricated just prior the start of each test.

10.3 *Assembly of the Spiral Orbit Tribometer:*

10.3.1 Test under vacuum or appropriate atmosphere at room temperature

10.3.1.1 First test:

(1) Open the door of the SOT.

(2) Fix the upper disk.

(3) Fix the lower disk

*(4)*Attach the guide plate to its holder.

(5) Tighten the guide plate holder with its guide plate to the force transducer.

(6) Place the ball on the lower plate and in contact with the guide plate.

(7) Apply the selected load for the test.

(8) Rotate the rotary plate so as there is no contact between the guide plate and the ball.

(9) Close the door of the SOT.

(10) Set the speed of the test with the motor controller.

(11) Start the roughing and turbomolecular pumps.

(12) Turn on the pressure gauge.

(13) Wait until the pressure drops below 1.3E-6 Pa if the test is a vacuum test.

(14) Start the test.

(15) When the test is finished, write down the number of orbits performed.

(16) Calculate the normalized lifetime.

10.3.1.2 *Second and sequential tests.*

(1) Open the door of the SOT.

(2) Unload the system.

(3) Remove the ball.

(4) Place the ball on a handling tool.

(5) Remove the guide plate holder from the force transducer.

(6) Remove the guide plate from the holder.

(7) Place the guide plate on its dedicated holder.

(8) Place a new guide plate on the guide plate holder.

(9) Place a 1 mm thick washer on the screw of the force transducer to advance the position of the guide plate, establishing a new track on the fixed and rotary plates. If more than 4 tests are to be performed, a fresh set of plates should be used to prevent a reduction in the diameter of the spiral beyond 4 tests.

(10) Tighten the guide plate holder with its guide plate to the force transducer

(11) Place a new lubricated ball with pristine lubricant on the lower plate and in contact with the guide plate.

(12) Apply the selected load for the test.

(13) Rotate the rotary plate so as there is not contact between the guide plate and the ball.

(14) Ground the piezoelectric charge amplifier.

(15) Close the door of the SOT.

(16) Start the roughing and turbomolecular pumps.

(17) Turn on the pressure gauge.

(18) Wait until the pressure drops below 1.3E-6 Pa if the test is a vacuum test.

(19) Start the test.

(20) When the test is finished, record the number of orbits performed.

(21) Calculate the normalized lifetime.

10.4 *Data collection and treatment*—The SOT should be interfaced to a data acquisition computer to continuously record several parameters, such as the friction coefficient, the load applied, the pressure within the vacuum chamber (if applicable), the temperature (if applicable), and the resistance across the ball-disks contacts (optional). This data can be stored in a file, and one file can be created for each test.

11. Calculation or Interpretation of Results

11.1 *Friction Coefficient*

$$Coefficient\ of\ Friction = C_oF = \frac{F_{gp}}{2 \times load} \quad (1)$$

where:

F_{gp} = force exerted by the ball on the guide plate, and measured by the force transducer attached to the guide plate.

load = load applied between the plates to maintain the ball between them.

11.2 *Normalized Lifetime*—The normalized lifetime for one test of a lubricant is obtained by calculating the number of orbits performed before the friction coefficient limit is reached divided by the total amount of lubricant put on the ball (in µg) at the beginning of the test. An average is made over a minimum of four normalized lifetimes obtained after running four tests for the lubricant to be evaluated. More sample tests may be run to eliminate outliers and to determine the standard deviation in the performance of the samples.

12. Report

12.1 *The following data should be included in the test report:*

12.1.1 The type of lubricant evaluated.

12.1.2 The amount (in μg) of the lubricant deposited on the ball, and the technique used to lubricate the ball.

12.1.3 The materials of the fixed plate, rotary plate, ball, guide plate used and the technique used to clean them. The surface roughness, hardness and condition such as passivation if applicable.

12.1.4 The atmosphere the test was run in, the temperature of the test, the load applied, the speed.

12.1.5 The initial steady state friction coefficient, the total number of orbits performed, the cut-off friction coefficient, the normalized lifetime, and the standard deviation obtained.

12.2 *Two charts should be plotted in the test report:*

12.2.1 The first chart will include the friction traces of the tests conducted for the lubricant.

12.2.2 The second chart will be the average normalized lifetime of the lubricant with its standard deviation.

13. Precision and Bias

13.1 *Normalized lifetime*—Experiments have shown that carefully conducted tests with lubricants of a different nature have produced coefficient of variation of 30 % or less for normalized lifetime on the SOT (See Fig. 1).

13.2 Friction coefficients of material couples obtained on the SOT may be different from coefficients of the same material couples tested on a different apparatus. A friction coefficient is a system effect, so appropriate caution must be used when comparing or using data from different sources and systems.

13.3 This is an interim standard and precision and bias data have not been collected or reported. An effort to construct a standard test and collect inter-laboratory data is underway.

14. Keywords

14.1 accelerated testing; boundary lubrication; fluid lubricants; friction coefficient; greases; tribology; relative lifetimes; vacuum tribology

ANNEX

(Mandatory Information)

A1. MEASUREMENT OF FRICTION COEFFICIENT

A1.1 The following analysis is from S. V. Pepper and E. P. Kingsbury.[4] This paper describes how the SOT measures the friction coefficient from the force experienced by the guide plate normal to its face. For this, expressions for the ball's angular velocity during both the spiral orbit and the scrub zone were developed. The analysis determines the locus of slip between the ball and plates and ultimately indicates the relationship between the friction coefficient and the guide plate force. The analysis is based on roll without slip between rigid bodies, meaning no relative linear velocity exists at the ball-plate contact. This is required because rolling friction is an order of magnitude smaller than sliding friction, even for the most favorable boundary lubricated conditions. The roll without slip condition is satisfied at all contacts in the system except between the ball and the rotating plate in the scrub region. This contact in the scrub between the ball and the rotating plate exhibits gross sliding. The analysis shows that the force on the guide plate, normal to its face, is twice the friction force generated by the ball sliding on the rotating plate. This establishes the ability of the SOT to measure the friction force by the transducer on which the guide plate is mounted. The coefficient of friction (CoF) is then obtained by dividing this friction force by the load:

$$C_oF = \frac{F_{gp}}{2 \times load} \quad (A1.1)$$

A plot of the guide plate force versus time of the ball in the scrub is shown in Fig. A1.1. The guide plate force has already been divided by 2 to obtain the friction force indicated on the ordinate. The region in which the friction force is obtained for the calculation of the CoF is indicated by the heavy horizontal bar. This procedure is explained in the reference cited above.

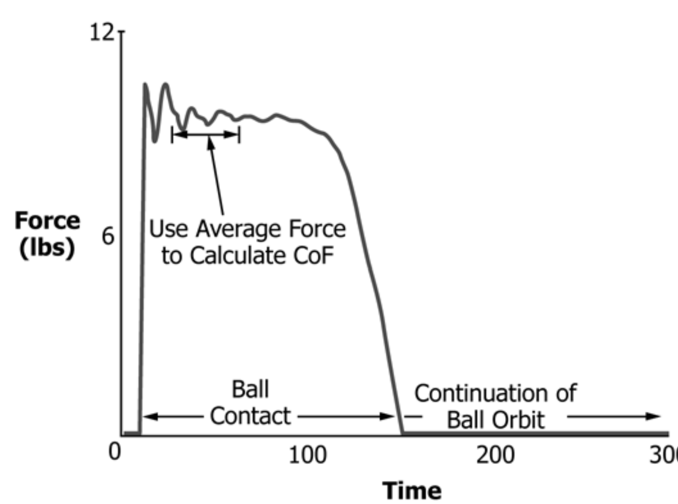


FIG. A1.1 Typical guide plate force profile from the SOT

[4] S. V. Pepper and E. P. Kingsbury, "Spiral Orbit Tribometry – Part II: Evaluation of Three Liquid Lubricants in Vacuum," *Trib. Trans.* 46,57(2003).

A1.2 The friction is measured only during ~ 5 % of the orbit traversed by the ball. There may also be forces on all the elements that are tangential to the guide plate's face. However, the force transducer only senses forces normal to the guide plate's face, so that forces tangential to the guide plate's face are not considered further here.