Standard Guide for
Instrument and Precision Bearing Lubricants—Part 1 Oils[1]

1. Scope

1.1 This guide is a tool to aid in the choice of an oil for precision rolling element bearing applications. There are two areas where this guide should have the greatest impact: (*1*) when a lubricant is being chosen for a new bearing application and (*2*) when a lubricant for a bearing has to be replaced because the original lubricant specified for the bearing can no longer be obtained. The Report (Section 5) contains a series of tests performed by the same laboratory on a wide variety of oils commonly used in bearing applications to allow comparisons of those properties of the oil that the committee thought to be most important when making a choice of lubricant. This guide contains a listing of the properties of oils by chemical type, that is, ester, silicone, and so forth. This organization is necessary since the operational requirements in a particular bearing application may limit the choice of lubricant to a particular chemical type due to its temperature stability, viscosity index or temperature-vapor pressure characteristics, and so forth. The Report includes the results of tests on the oils included in this study. The Report recommends replacement lubricants for those oils tested that are no longer available. The Report also includes a glossary of terms used in describing/discussing the lubrication of precision and instrument bearings. The Report presents a discussion of elastohydrodynamic lubrication as applied to rolling element bearings.

1.2 Although other compendia of lubricant properties have been published, for example, the Barden Product Standard, Lubricants[2] and the *NASA Lubricant Handbook for the Space Industry*[3], none have centered their attention on lubricants commonly used in precision rolling element bearings (PREB). The PREB put a host of unique requirements upon a lubricant. The lubricant must operate at both high and low temperatures. The lubricant must provide lubrication for months, if not years, without replenishment. The lubricant must be able to support high loads but cannot be so viscous that it will interfere with the operation of the bearing at very high speeds or low temperatures, or both. The lubricant must provide boundary lubrication during low-speed or intermittent operation of the bearing. And, in many applications, its vapor pressure must be low enough under operating conditions that evaporative losses do not lead to lubricant depletion or contamination of nearby components. These and other considerations dictated the series of tests that were performed on each lubricant included in this study.

1.3 Another important consideration was encompassed in this study. Almost all of the testing was performed by the same laboratory, The Petroleum Products Research Department of the Southwest Research Institute in San Antonio, Texas, using ASTM procedures. This continuity of testing should form a solid basis for comparing the properties of the multitude of lubricants tested by avoiding some of the variability introduced when lubricants are tested by different laboratories using different or even the "same" procedures.

1.4 It should be noted that no functional tests (that is, bearing tests) were performed. The results of the four-ball wear test give some comparison, "a figure of merit," of the lubrication properties of the oils under the condition of this test. But experience has shown that testing the lubricant in running bearings is the best means of determining lubricant performance.

2. Referenced Documents

2.1 *ASTM Standards:*[4]

D92 Test Method for Flash and Fire Points by Cleveland Open Cup Tester
D97 Test Method for Pour Point of Petroleum Products
D445 Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)
D974 Test Method for Acid and Base Number by Color-Indicator Titration

---

[1] This guide is under the jurisdiction of ASTM Committee F34 on Rolling Element Bearings and is the direct responsibility of Subcommittee F34.02 on Tribology and was developed by DoD Instrument Bearing Working Group (IBWG) former F34.

Current edition approved Jan. 1, 2010. Published February 2010 originally approved in 2001. Last previous edition approved in 2001 as F2161–01. DOI: 10.1520/F2161-10.

[2] *Product Standard, Lubricants* , available from The Barden Corp., Danbury, CT.

[3] NASA Lubricant Handbook for the Space Industry, Ernest L. McMurtrey , *NASA Technical Memorandum TM-86556*, George C. Marshall Space Flight Center, National Aeronautics and Space Administration, December 1985.

[4] 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.

D972 Test Method for Evaporation Loss of Lubricating Greases and Oils

D1331 Test Methods for Surface and Interfacial Tension of Solutions of Paints, Solvents, Solutions of Surface-Active Agents, and Related Materials

D2270 Practice for Calculating Viscosity Index from Kinematic Viscosity at 40 and 100°C

D4172 Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method)

2.2 *Government Documents*[5]:

MIL-DTL-53131 Lubricating Oil, Precision Rolling Element Bearing, Plolyalphaolefin Based

MIL-L-6085 Lubricating Oil, Aircraft Turbine Engine, Synthetic Base

MIL-L-14107 Lubricating Oil, Weapons, Low Temperature

MIL-L-23699 Lubricating Oil, Aircraft Turbine Engines, Synthetic Base

MIL-L-7808 Lubricating Oil, Aircraft Turbine Engine, Synthetic Base

MIL-L-81846 Lubricating Oil, Instrument, Ball Bearing, High Flash Point

MIL-S-81087 Silicone, Fluid, Chlorinated Phenyl Methyl Polysiloxane

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *ABEC, n*—Annular Bearing Engineer's Committee of the American Bearing Manufacturers Association (ABMA). The ABEC establishes bearing tolerance classes. Precision bearings are ABEC 5P and ABEC-5T and higher.

3.1.2 *absolute viscosity* (η)*, n*—(sometimes called dynamic viscosity or just viscosity)—a measure of the tendency of the fluid to resist shear. The elastohydrodynamic theory (EHD) film thickness and torque losses in a ball bearing are very strong functions of η. Since the ratio of absolute viscosity to density, η/ρ, appears frequently in hydrodynamic analyses, it was given its own name, kinematic viscosity, ν. The cgs unit of viscosity is the centipoise (cP). The SI unit of viscosity is the Pascal-s (Pa-s).

Absolute viscosity is defined for a Newtonian fluid as follows. The shear stress at any point in the fluid is proportional to the rate of shear. The proportionality constant is called the absolute viscosity. Viscosity is thus defined by the force, *F*, to move one surface of area, *A*, with respect to another surface separated by a fluid film, *h*, at a speed, *U*, through the following relationship:

$$\eta = (F/A)(h/U)$$

The value of the absolute viscosity changes greatly with temperature, *T*. As the temperature increases viscosity decreases. ASTM International has adopted the following relationship between kinematic viscosity and temperature:

$$\log_{10} \log_{10}(\nu + 0.8) = m \log_{10} T + c$$

where:

m and c = constants for each fluid.

ASTM International supplies chart paper with the ordinate proportional to $\log_{10}\log_{10}(\nu + 0.8)$ and with the abscissa proportional to $\log_{10} T$. Thus the values of kinematic viscosity versus temperature can be plotted as a straight line on the paper allowing extrapolation of values intermediate to those that have been measured.

Absolute viscosity is a weak function of the pressure imposed upon the fluid. However, the pressures generated in the ball-race contact zone of a ball bearing can be on the order of 10^3 GPa (10^5 psi) and at these pressures significant increases in viscosity can occur. Experiments have shown that viscosity varies exponentially with pressure and can be expressed as follows:

$$\eta = \eta_0 \exp(\alpha p)$$

where:

η_0 = viscosity at a pressure of one atmosphere,
p = pressure, and
α = pressure-viscosity coefficient.

A table of values of α for some common classes of bearing lubricants can be found after the definition of pressure-viscosity coefficient included in this glossary.

Recent work has shown that the viscosity changes with temperature can also be modeled by an exponential relationship. Thus, viscosity at any pressure and temperature can be expressed as follows:

$$\eta_{T,\,p} = \eta_0 \exp(\alpha p + \beta(1/T + 1/T_0))$$

where:

β = temperature-viscosity coefficient.

3.1.3 *acid number, n*—a measure of the quality of a lubricant. High acid numbers (much higher than the fresh oil) are an indication of lubricant oxidation/degradation. Oils with high acid numbers should not be used. Acid number is measured as milligrams of KOH needed to neutralize one gram of oil.

3.1.4 *additive, n*—any chemical compound added to a lubricant to improve or meet special needs necessary for service (formulated lubricants). The most important additives are antioxidants, rust and corrosion inhibitors, and extreme pressure (EP) and antiwear (AW) additives.

3.1.5 *antioxidants* (oxidation inhibitors)*, n*—chemical compounds used to improve the oxidation stability and subsequent deterioration of lubricants.

3.1.6 *boundary lubrication, n*—a condition of lubrication in which the friction between two surfaces in relative motion is determined by the roughness of the surfaces and by the properties of the lubricant other than viscosity. Antiwear and extreme pressure additives reduce the wear of components operating under this regime.

3.1.7 *centipoise, n*—a unit of dynamic viscosity. The unit in the cgs system is one centipoise (cP). The SI unit of dynamic viscosity is 1 Pa-s and equivalent to 10^3 cP.

---

[5] Available from Document Automation and Production Service, Building 4/D, 700 Robins Ave., Philadelphia, PA 19111–5094.

3.1.8 *centistoke, n*—a unit of kinematic viscosity. The unit in the cgs system is one centistoke (cSt). The SI unit of kinematic viscosity is 1 m^2/s and is equivalent to 10^6 cSt.

3.1.9 *compatibility, n*—a measure of the ability of a lubricant to be mixed with other lubricants or bearing preservatives (fluids that form films on metal surfaces to prevent corrosion during storage) to form a uniform mixture without causing any resultant reaction or precipitation of material. Compatibility is also a measure of the ability of a lubricant not to cause any detrimental effect to metal, plastic, or elastomer materials.

3.1.9.1 *Discussion*—It is recommended that any preservative material be removed from bearings before lubrication.

3.1.10 *contamination, n*—(*1*) The presence of mostly solid foreign materials like sand, grinding powder, dust, and so forth, in a lubricant that might cause an increase in wear, torque, and noise and result in reduced bearing life. (*2*) The presence of fluids like water, solvents, and other oils that might cause accelerated oxidation, washout, rusting, or crystallization of the additives and other phenomena that reduce a bearing's life.

3.1.11 *corrosion, n*—the gradual destruction of a metal surface due to chemical attack caused by polar or acidic agents like humidity (water), compounds formed by lubricant deterioration, or by contaminants from the environment.

3.1.12 *corrosion inhibitors, n*—corrosion inhibitors protect metal surfaces against corrosion or rust by forming a protective coating or by deactivation of corrosive compounds formed during the operation of a bearing.

3.1.13 *density, n*—the mass per unit volume of a substance. The cgs unit of density (ρ) is 1 g/cm^3, and the SI unit of density is 1 kg/m^3. Density depends on the chemical composition and in itself is no criterion of quality. It is a weak function of temperature and pressure for liquids and solids.

3.1.14 *DN value, n*—the product of the bearing bore diameter in millimetres multiplied by the speed in revolutions per minute (compare to nD_m-value).

3.1.15 *dynamic viscosity, n*—another name for absolute viscosity.

3.1.16 *elastohydrodynamic theory (EHD), n*—See Appendix X1.

3.1.17 *EP lubricants (extreme pressure lubricants), n*—lubricants (oil or greases) that contain extreme pressure additives to protect the bearings against wear and welding (scoring).

3.1.18 *esters, n*—esters are formed from the reaction of acids and alcohols. Esters form a class of synthetic lubricants. Esters of higher alcohols with divalent fatty acids form diester lubricants while esters of polyhydric alcohols are called the polyol ester lubricants. These latter esters have higher viscosity and are more heat-resistant than diesters.

3.1.19 *evaporation loss, n*—lubrication fluid losses occurring at higher temperatures or under vacuum, or both, due to evaporation. This can lead to an increase in lubricant consumption and also to an alteration of the fluid properties of a lubricant (especially an increase in the viscosity of blended lubricants). The evaporation loss is expressed as a weight loss in milligrams (10^{-6} kg) or wt %.

3.1.20 *fire point, n*—the lowest temperature at which the vapor or a lubrication fluid ignites under specified test conditions and continues to burn for at least 5 s without the benefit of an outside flame. The fire point is a temperature above the flash point. Perfluoropolyethers have no fire point.

3.1.21 *flash point, n*—the lowest temperature of a lubrication fluid at which the fluid gives off vapors that will ignite when a small flame is periodically passed over the liquid surface under specified test conditions. The flash and fire points provide a rough characterization of the flammable nature of lubrication fluids. Perfluoropolyethers have no flash point.

3.1.22 *four-ball tester, n*—a tester used to evaluate the wear behavior of lubricants under extreme pressure. Four steel balls are arranged in a pyramidal shape. During the test, the three balls comprising the base of the pyramid are stationary while the upper ball rotates. The lubricant sample is placed in the ball pot. The average wear scar (measured in millimetres) formed on the stationary balls is reported.

3.1.23 *fretting corrosion, n*—a special type of wear produced on materials in intimate contact that are subjected to the combined action of oscillatory motions of small amplitudes and high frequencies. Fretting corrosion appears similar to atmospheric corrosion (rust) as a reddish-brown layer on steel surfaces.

3.1.24 *interfacial tension, n*—when two immiscible liquids are in contact, their interface has many characteristics in common with a gas-liquid surface. This interface possesses interfacial free energy because of the unbalanced attractive forces exerted on the molecules at the interface by the molecules within the separate phases. This free energy is called the interfacial tension.

3.1.25 *instrument bearings, n*—all bearings whose outer diameter is 30 mm or less, as defined by The American Bearing Manufacturers Association (ABMA).

3.1.26 *kinematic viscosity, n*—the ratio of absolute viscosity to fluid density. This ratio arises frequently in lubrication analyses and thus kinematic viscosity has become a separate term describing the viscosity of a fluid. Many experimental measurements of viscosity of fluids result in a measure of kinematic viscosity from which absolute viscosity is calculated. See *absolute viscosity*. The cgs unit of kinematic viscosity is cSt, and the SI unit is m^2/s. The viscosity of a PREB oil is a major factor in lubricant selection. The viscosity is directly involved in frictional, thermal, and fluid film conditions which reflect the influence of load, speed, temperature, and design characteristics of the bearing being lubricated.

3.1.27 *military (MIL) specifications, n*—specifications of the U.S. Armed Forces indicating the minimum mandatory requirements for an item that is to be procured. Military specifications are widely used as procurement requirements and as a quality standard.

3.1.28 *mineral oil, n*—oils based on petroleum stocks. These oils come in two types, naphthenic and paraffinic. The naphthenic oils contain unsaturated hydrocarbons, usually in the form of aromatic species. The paraffinic oils are primarily saturated hydrocarbons with only low levels of unsaturation.

3.1.29 *nD_m-value (index), n*—also called speed index—a relative indicator of the lubricant stress imposed by a bearing rotating at a given speed, where n is the rotational speed of the rolling element bearing in revolutions per minute and D_m is the mean diameter in millimetres (arithmetic mean of bore diameter d and outside diameter D). The speed index is multiplied by a factor k_a depending on the roller element bearing type:

k_a = 1 for deep groove ball bearings, angular contact ball bearings, self-aligning ball bearings, radially loaded cylindrical roller bearings, and thrust ball bearings,
k_a = 2 for spherical roller bearings, taper roller bearings, and needle roller bearings, and
k_a = 3 for axially loaded cylindrical roller bearings and full complement roller bearings.

The factor k_a takes into account the various rates of sliding friction that usually occurs during the operation of a rolling element bearing. The nD_m-value is an aid in choosing a suitable lubricant viscosity for a given bearing speed and is particularly applicable to grease-lubricated bearings.

3.1.30 *neutralization number, n*—a measure of the acidity or alkalinity of a lubricating fluid. The test determines the quantity of base (milligrams of potassium hydroxide) or acid (also expressed as milligrams of potassium hydroxide) needed to neutralize the acidic or alkaline compounds present in a lubricating fluid. Actually, the neutralization number is not one number but several numbers: strong acid number, total acid number, strong base number, and total base number. The neutralization number is used for quality control, and to determine changes that occur in a lubricant in service.

3.1.31 *oxidation stability, n*—the stability of a lubricant in the presence of air or oxygen is an important chemical property. Oxidation stability has a strong influence on numerous physical properties of a lubricant. These properties include the change of viscosity under static conditions for long periods of time (storage) or when exposed to temperatures high above room temperature, or both. The slow chemical reaction of fluid (base oil) and oxygen (air) is called oxidation. Inhibitors (see *antioxidants*) are used to improve the oxidation stability of the lubricants. Synthetic fluids, especially perfluoropolyethers and silicones, are much more resistant to oxidation than mineral oils.

3.1.32 *precision bearings, n*—regardless of size, the class of bearings used in instrument types of applications and with similar tolerances as instrument bearings. Bearings usually used in these applications are of high quality and are not put under high stress, thus they usually do not fail under fatigue.

TABLE 1 Pressure-Viscosity Coefficients for the Lubricant Classes Covered in This Guide

Oil Type	α^A (GPa^{-1})
Mineral oil (paraffinic-naphthenic)	21
Mineral oil (naphthenic-aromatic)	30
Polyalphaolefin	18
Diester-(2-ethylhexyladipate)	7.6
Polyolester (pentaerythritolvalerate)	7.5
Polydimethylsilicone (1000 mm^2/s at 40°C)	2.3
PFPE–linear	4–12
PFPE–branched	26–36

[A] 1 atm = 0.001013 GPa.

3.1.33 *perfluoropolyethers (PFPE or PFAE), n*—fully fluorinated long-chain aliphatic ethers. The perfluoropolyethers show some extraordinary properties like chemical inertness, nonflammability, high thermal and oxidative resistance, very good viscosity-temperature characteristics, and compatibility with a wide range of materials, including metals and plastics. The perfluoropolyethers, however, are not suitable for use with aluminum, magnesium, and titanium alloys. The perfluoropolyethers are not compatible with other types of synthetic fluids and mineral oils and cannot dissolve common lubricant additives.

3.1.34 *pH value, n*—a scale for measuring the acidity or alkalinity of a product. Zero pH is very acid, 7 is neutral, and 14 is very alkaline.

3.1.35 *poise (P), n*—See *centipoise* (cP).

3.1.36 *pour point, n*—(of a lubricating fluid)—the lowest temperature at which the lubricating fluid will pour, or flow.

3.1.37 *pressure-viscosity coefficient, n*—the dynamic viscosity of a fluid increases with increasing pressure. The dependence of viscosity (absolute), η, on pressure, p, can be expressed by the equation:

$$\eta = \eta_0 \exp(\alpha p)$$

where:

η = absolute viscosity at pressure, p,
η_0 = absolute viscosity at one atmosphere, and
α = the pressure-viscosity coefficient.

The pressure-viscosity coefficient is very small and varies with the chemical composition of the fluid. Some values of α for the classes of lubricants discussed in the Report section are given in Table 1.[6]

One limitation of the use of η_0 and the corresponding equation is that the measurements of η_0 are made under static conditions where the pressure is held constant while the viscosity attains a steady-state value. In actual bearing operations, the lubricant may see high pressure in the contact zone for only a few milliseconds and the viscosity changes due to this high pressure may not reach steady-state values.

3.1.38 *rated viscosity, (ν_1), n*—the kinematic viscosity attributed to a defined lubricating condition of a rolling element bearing. The rated viscosity is a function of the speed and can be determined by the mean bearing diameter in millimetres (10^{-3} m) and the rotational speed (rpm). More details can be found in Appendix X1.

3.1.39 *repeatability, n*—a criterion for judging the acceptability of test results. Repeatability is the difference between successive test results obtained by the same operator with the same apparatus under constant operating conditions on identical test material. Repeatability is usually reported as a range of values that would, in the normal and correct operation of the test method, encompass two standard deviations from the median value of the test.

---

[6] *Journal of Synthetic Lubrication* , Vol 1, 1984, pp. 73-86.

3.1.40 *reproducibility, n*—a criterion for judging the acceptability of test results. Reproducibility is the difference between two single and independent results, obtained by different operators working with identical test material. This difference, in the long run and under normal and correct operation of the test method, would not exceed a specified value.

3.1.41 *saponification number, n*—a measure of the amount of constituents of a lubrication fluid that will easily saponify under test conditions. The saponification number is expressed in milligrams of potassium hydroxide that are required to neutralize the free and bonded acids contained in one gram of lubricating fluid. The saponification number is a measure of fatty acids compounded in an oil and a measure of the state of oil deterioration.

3.1.42 *saponify, v*—to hydrolyze an ester and to convert the free acid into soap.

3.1.43 *seal compatibility, n*—the extent of the reaction of sealing materials with lubricating oils, greases, and other fluids. The reaction can result in swelling, shrinking, plasticizing, embrittlement, or even dissolution. Operating temperatures and lubricant composition are dominant factors influencing the extent of the interaction between the sealing material and the lubricating fluid.

3.1.44 *setting point, n*—of a lubricating fluid—the temperature at which the fluid ceases to flow when cooled under specified conditions. The low-temperature behavior of the fluid slightly above the setting point may be unsatisfactory and, therefore, this behavior should be determined by measuring the low-temperature kinematic or absolute viscosity.

3.1.45 *shelf life, n*—the expression shelf life of a lubricant is not exactly specified. Two versions of the definition exist:

(*1*) *shelf life*—the ability of a lubricated part to function even after long-term storage. This definition is very critical because it includes not only the aging properties of the lubricant used but also the loss of lubricant due to evaporation and creeping.

(*2*) *shelf life*—the storage stability of the bulk lubricant in its original container. Stability is defined here as no change in the physical or chemical properties of the lubricant.

3.1.46 *silicone oils, n*—synthetic fluids composed of organic esters of long chain complex silicic acids. Silicone oils have better physical properties than mineral oils. However, silicone oils have poorer lubrication properties, lower load-carrying capacity, and a strong tendency to spread on surfaces (see *surface tension*). To prevent this spreading the use of barrier films is necessary.

3.1.47 *stability, n*—the resistance of a lubricant to a change in its properties after being stored for a defined period of time. The methods to test a lubricant for stability are defined in individual military or commercial specifications.

3.1.48 *surface energy/surface tension, n*—a fundamental property of liquids is the existence of a free energy at the surface. A consequence of this free energy is the property that a liquid spontaneously contracts to the smallest possible area. For example, liquid droplets assume a spherical shape if no outside forces are acting on the droplet. To deform the droplet from its spherical shape, a definite amount of work must be done. This work (or energy expended) when normalized per unit area is called surface tension and has the unit mN/m (formally dyne/cm). Surface tension is dependent upon temperature but not upon pressure. The surface tension is a measure for the wetting of a bearing surface and for the creeping (spreading) property of a lubricant. Fluids with low surface tensions like dimethylsilicones show improved wetting but increased creeping (migration) tendency.

3.1.49 *swelling properties, n*—the swelling of natural rubber and elastomers under the influence of lubricants.

3.1.50 *synthetic fluids, n*—lubricating fluids produced by chemical synthesis. The synthetic route to lubricants allows the manufacturer to introduce those chemical structures into the lubricant molecule that will impart specific properties into the resultant fluid such as very low pour point, good viscosity-temperature relationship, low evaporation loss, long lubricating lifetime, and so forth.

3.1.51 *viscosity, n*—See *absolute viscosity*.

3.1.52 *viscosity index (VI), n*—indicates the range of change in viscosity of a lubricating fluid within a given temperature range. With an increase in the viscosity index, the fluid becomes less sensitive to temperature, that is, a low-viscosity index signifies a relatively large change, whereas a high-viscosity index relates to a relatively small change in viscosity with temperature.

3.1.53 *wear, n*—the attrition or rubbing away of the surface of material as a result of mechanical action.

4. Significance and Use

4.1 The purpose of this guide is to report on the testing of, to discuss and compare the properties of, and to provide guidelines for the choice of lubricants for precision rolling element bearings (PREB). The PREB are, for the purposes of this guide, meant to include bearings of ABEC 5 quality and above. This guide limits its scope to oils used in PREB and is to be followed by a similar document to encompass greases used in PREB.

4.2 The number of lubricants, both oils and greases, used in PREB increased dramatically from the early 1940s to the mid 1990s. In the beginning of this period, petroleum products were the only widely available base stocks. Later, synthetic lubricants became available including synthetic hydrocarbons, esters, silicones, and fluorinated materials, including perfluorinated ethers and the fluorosilicones. This broad spectrum of lubricant choices has led to the use of a large number of different lubricants in PREB applications. The U.S. Department of Defense, as a user of many PREB, has seen a significant increase in the logistics effort required to support the procurement and distribution of these items. In addition, as time has passed some of the lubricants used in certain PREB are no longer available. The SRG Series, LSO-26, and Teresso V-78 are examples of such lubricants. This implies that replacement lubricants must be found as, in this era of extending the lifetime of DoD assets, stockpiles of replacement parts become depleted.

4.3 One of the primary goals of this study was to take a broad spectrum of the lubricants used in PREB and do a comprehensive series of tests on them in order that their properties could be compared and, if necessary, potential replacement lubricants identified. This study is also meant to be a design guide for choosing lubricants for PREB applications. This guide represents a collective effort of many members of this community who span the spectrum from bearing manufacturers, original equipment manufactures (OEMs), lubricant manufacturers and suppliers, procurement specialists, and quality assurance representatives (QARs) from DoD and end users both inside and outside DoD.

5. Report

5.1 Tables 2-6[7] give the test results of the 44 PREB oils tested. Each oil was tested for kinematic viscosity, pour point, flash point, evaporation loss, surface tension, four-ball wear, and acid number. In addition, a viscosity index was calculated for each of the oils tested by using the kinematic viscosities at 40°C and 100°C in cSt and using the following formula:

$$VI = (L - U)/(L - H) \times 100$$

where:

VI = viscosity index,
U = viscosity at 40°C of the oil tested, and
H and L = the viscosities of viscosity index reference oils (VI = 100 and VI = 0, respectively) at 40°C in accordance with Practice D2270.

The preceding method for obtaining VI is not appropriate if it results in a VI >100. For VI values above 100, an empirical fit was developed to yield the following equation:

$$VI = (10^N - 1)/7.15 \times 10^{-3} + 100$$

where:

N = (log H – log U) / log Y, where Y is the viscosity of the oil of interest, cSt at 100°C.

All of the testing of the oils was done by the Petroleum Products Research Department of the Southwest Research Institute in San Antonio, Texas using ASTM procedures.

6. Recommendations and Conclusions

6.1 The 44 oils tested were divided into 5 different chemical classifications (mineral oils, polyalphaolefins, esters, silicones, and perfluorinated aliphatic ethers). It is concluded that many of the oils within a given classification (and between classifications) have similar physical properties, and comparison of these properties can be a useful first step in selecting oil candidates for a given application. The data may also be useful when selecting alternate lubricants to replace one that is no longer available or to reduce the number of oils kept in inventory.

6.1.1 By chemical classification the committee recommends the following:

6.1.1.1 *Mineral Oils*—The use of mineral oils is, in general, not recommended. These oils can vary from lot to lot depending upon the source of the crude oil used as feedstock and upon the exact chemical and physical processes used to refine the feedstock. The main advantage of mineral oils over synthetic hydrocarbon oils is cost. In most PREB applications, the cost of using either type of lubricant is usually a very small part of the overall cost of the bearing. Therefore, in most PREB applications, the differential cost of using a mineral oil versus a PAO (synthetic hydrocarbon) should not be a determining factor in the choice of oil.

6.1.1.2 *Polyalphaolefins*—The synthetic hydrocarbon base stocks (PAOs) are very similar in chemical structure to paraffinic mineral oils yet have the advantage of being synthesized. Synthetically producing an oil gives the manufacturer considerably more control over its chemical composition and thus controls the variability from lot to lot. The use of PAOs is recommended for many PREB applications. The PAOs exhibit many of the physical properties that are required for the lubrication of PREB and have a history of being used successfully in PREB. If the use of a PAO is deemed appropriate for

TABLE 2 Properties of PREB Mineral-Based Oils

Mineral Oils[A]	Properties Density (0.87 – 0.91 g/cm^3) (0.87 – 0.91 × 10^3 kg/m^3)									
	Kinematic Viscosity [cSt] (10^{-6}m^2/s)[B]									
	40°C	100°C	Low Temperature	Viscosity Index (VI)	Pour Point[C] [°C]	Flash Point[D] [°C]	Evaporation Loss[E] [% wt]	Surface Tension[F] (22°C) [dyne/cm]	4-Ball Wear [MN/m] or [mm]	Acid Number [mg KOH/g]
S-1	97.00	9.13	ND[G]	63.6	-20	196	8.24	28.86	0.70	0.04
S-2[H]	24.75	4.61	3039 (-20°C)	100	-33	143	24.07	26.31	0.58	0.05
S-3[H]	83.35	10.41	1557 (-5°C)	107	-18	199	3.88	25.95	0.54	0.06
S-4[H]	135.00	14.80	2300 (0°C)	110	-7	265	0.59	28.66	0.55	0.03
S-5[H]	42.00	6.50	ND[G]	105	-7	201	2.13	28.4	0.78	0.22
S-6[H]	131.29	14.19	1710 (0°C)	106	-12	191	4.10	24.86	0.58	0.11

[A] The product names are listed in RR:F34-1001.[7]
[B] Test Method D445
[C] Test Method D97
[D] Test Method D92
[E] Test Method D972
[F] Test Methods D1331
[G] Not determined.
[H] No longer available.

---

[7] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:F34-1001.

TABLE 3 Properties of PREB PAO-Based Oils

Polyalphaolefins (PAOs) (Synthetic Hydrocarbons)[A]	Properties Density (0.82 – 0.85 g/cm^3)									
	Kinematic Viscosity, mm^2/s									
	40°C	100°C	Low Temperature	Viscosity Index (VI)	Pour Point [°C]	Flash Point [°C]	Evaporation Loss [% wt]	Surface Tension (22°C) [dyne/cm]	4-Ball Wear [MN/m] or [mm]	Acid Number [mg KOH/g]
S-7	29.00	5.50	ND[B]	129	-66	238	4.63	26.10	1.23	0.02
S-8	27.92	5.55	18 630 (-54°C)	141	-67	246	1.67	23.28	ND[B]	0.47
S-9	28.69	5.50	16 940 (-64°C)	132	-66	238	2.86	26.13	0.77	0.10
S-10	30.00	5.90	ND[B]	145	-54	227	3.25	26.50	0.75	0.26
S-11	16.52	3.82	17 469 (-52°C)	124	<-59	221	2.37	28.08	0.67	0.01
S-12	386.1	38.93	52 000 (-20°C)	150	-45	243	0.36	28.48	0.28	0.02
S-13	386.6	38.60	52 000 (-20°C)	148	-42	238	0.66	30.00	0.32	0.02
S-14	390	39.0	52 000 (-20°C)	149	-40	240	0.89	28.30	0.40	0.06
S-15	29.82	5.78	14 142 (-47°C)	140	-57	246	1.06	29.75	0.64	0.01
S-16	67.53	10.66	14 673 (-33°C)	147	-54	261	1.29	27.72	0.63	0.11
S-17	112.1	15.52	25 856 (-36°C)	146	-46	261	0.68	29.75	0.60	0.02

[A] The product names are listed in RR: RR:F34-1001.[7]

[B] Not determined.

TABLE 4 Properties of PREB Ester-Based Oils

Esters[A]	Properties Density (0.92 – 1.01 g/cm^3)									
	Kinematic Viscosity, mm^2/s									
	40°C	100°C	Low Temperature	Viscosity Index (VI)	Pour Point [°C]	Flash Point [°C]	Evaporation Loss [% wt]	Surface Tension (22°C) [dyne/cm]	4-Ball Wear [MN/m] or [mm]	Acid Number [mg KOH/g]
S-18	12.54	3.50	10 949 (-54°C)	174	<-85	185	0.84	25.98	0.9	0.22
S-19[B]	13.08	3.48	10 604 (-54°C)	155	<-85	182	1.77	29.20	1.00	0.34
S-20	13.66	3.59	7269 (-52°C)	157	<-59	227	0.50	31.45	0.97	0.17
S-21	11.88	3.07	7269 (-54°C)	122	<-59	218	0.53	28.67	0.80	0.26
S-22	24.86	4.95	12 312 (-42°C)	126	-51	264	0.81	28.67	0.73	0.02
S-23	13.85	3.51	4637 (-54°C)	140	-66	243	0.44	28.10	1.12	0.65
S-24	12.11	3.30	8755 (-54°C)	154	<-75	213	3.46	27.76	0.96	0.22
S-25	24.31	5.01	4368 (-47°C)	136	-57	218	1.16	26.14	0.52	0.39
S-26	17.42	3.98	14 652 (-49°C)	127	<-59	245	1.99	29.63	0.70	0.18
S-27	36.01	6.60	21 878 (-42°C)	140	-59	273	1.96	28.89	0.80	0.28
S-28	50.95	8.40	13 169 (-37°C)	140	-51	285	0.47	29.34	0.69	0.01
S-29	48.69	8.65	40 492 (-39°C)	157	-54	266	1.97	28.64	0.37	0.42
S-30	12.66	3.42	8893 (-54°C)	158	-85	185	0.45	28.84	1.02	0.0

[A] The product names are listed in RR: RR:F34-1001.[7]

[B] No longer available.

a PREB application, the committee recommends that the initial choice of a lubricant be one that meets the MIL-DTL-53131 specification. This specification, which encompasses five viscosity grades, was written specially to provide an oil with the physical and chemical properties considered appropriate for most PREB applications. If a very low vapor pressure is a requirement for a PREB application, another new class of synthetic hydrocarbons, the alkylated cyclopentanes, may prove to be an alternative choice. Unfortunately, these fluids appeared after the conclusion of the testing phase of this guide and are not included in the oil database.

6.1.1.3 *Ester Oils*—This class of oils can be used in PREB applications. The main advantage is that ester oils have excellent lubricity and compatibility with a wide variety of additives. Ester oils also have somewhat better low-temperature behavior and are a little more resistant to thermo-oxidative degradation at temperatures above about 150°C than PAO oils. If these two advantages are not significant for a PREB application, a synthetic hydrocarbon may be substituted for an ester oil.

6.1.1.4 *Silicone Oils*—The use of silicone oils is not recommended in PREB unless the very high-viscosity index or the damping properties of these oils are critical to the PREB application. The very poor lubricity of silicone oils, tendency to creep, the fact that they can, under certain conditions, form glass-like, fairly hard deposits and, the difficulty in cleaning silicone oils from lubricated parts may be issues when considering silicone oils as a PREB lubricant.

6.1.1.5 *Perfluoropolyethers (PFPE)*—The use of PFPE oils in PREB is not recommended unless their very high-viscosity index, their very high thermo-oxidative stability, or their very low-vapor pressure are overriding concerns in the PREB application. The tendency to creep, the fact that the PFPE cannot be formulated with most of the effective lubricant

TABLE 5 Properties of PREB Silicone-Based Oils

Silicone Oils[A]	Properties Density (0.96 – 1.11 g/cm^3)									
	Kinematic Viscosity, mm^2/s									
	40°C	100°C	Low Temperature	Viscosity Index (VI)	Pour Point [°C]	Flash Point [°C]	Evaporation Loss [% wt]	Surface Tension (22°C) [dyne/cm]	4-Ball Wear [MN/m] or [mm]	Acid Number [mg KOH/g]
S-31	37.31	15.67	395 (-54°C)	432	-55	>696	1.08	18.81	2.34	0.01
S-32	37.24	14.81	993 (-54°C)	412	<-75	275	0.28	23.44	2.18	0.11
S-33	49.00	15.50	2500 (-54°C)	332	-75	288	0.64	19.34	1.13	0.10
S-34	208.11	31.01	6000 (0°C)	193	-15	300	0.06	29.93	5.03	0.05
S-35	71.17	20.65	13 988 (-54°C)	314	<-75	216	0.41	26.31	1.43	0.17
S-36	161.65	28.46	939 (-30°C)	216	-43	260	2.76	20.50	0.35	0.12

[A] The product names are listed in research report, RR: RR:F34-1001.[7]

TABLE 6 Properties of PREB Perfluoropolyether-Based Oils

Perfluoropolyethers[A]	Properties Density (1.87 – 1.90 g/cm^3)									
	Kinematic Viscosity, mm^2/s									
	40°C	100°C	Low Temperature	Viscosity Index (VI)	Pour Point [°C]	Flash Point [°C]	Evaporation Loss [% wt]	Surface Tension (22°C) [dyne/cm]	4-Ball Wear [MN/m] or [mm]	Acid Number [mg KOH/g]
Linear chain:										
S-37	18.11	6.04	1200 (-54°C)	329	<-75	ND[B]	1.45	23.0	0.58	0.04
S-38	145.00	45.00	1200 (-54°C)	347	<-75	ND[B]	0.02	21.0	1.20	0.01
S-39	154.20	47.26	4000 (-40°C)	346	<-66	ND[B]	0.04	21.9	1.00	0.04
S-40	226.18	23.36	21 000 (-15°C)	128	-36	ND[B]	0.27	21.5	1.46	ND[B]
S-41	27.72	4.74	9800 (-35°C)	87.4	-48	ND[B]	11.00	21.9	0.43	ND[B]
S-42	97.90	12.27	48 000 (-30°C)	118	-45	ND[B]	0.78	21.9	0.51	ND[B]
S-43	197.28	21.90	60 000 (-25°C)	134	-39	ND[B]	0.34	21.9	0.70	ND[B]
S-44	392.41	38.42	72 000 (-20°C)	145	-34	ND[B]	0.10	21.9	1.31	ND[B]

[A] The product names are listed in RR: RR:F34-1001.[7]

[B] Not determined.

additives, the PFPE poor boundary lubrication properties, and relatively high cost may be issues when considering PFPE as a PREB lubricant.

7. Keywords

7.1 ball bearings; ester oil; instrument and precision bearing lubricants; mineral oil; perfluoropolyether oil; polyalphaolefins; silicon oil

ANNEX

(Mandatory Information)

A1. PROPERTIES OF OILS—BASE STOCKS

A1.1 In the selection of a proper lubricating oil for a given operating condition it is necessary to know the characteristics of the base stock. Therefore, the main properties of the base stocks that are part of this guide will be discussed. It is also recommended that a review of the material safety data sheet be included in the selection process of a lubricant. This will allow an assessment of the health/handling risks associated with a particular oil.

A1.2 Mineral Oils

A1.2.1 *Use*—Multipurpose lubricant for large rolling element bearings, engines, gears, and so forth. These oils can be blended with polyalphaolefins (PAOs) or esters to improve their lubricity and temperature-viscosity characteristics.

A1.2.2 *Structure*—Due to the origin and the treatment of the base stocks, the formulated oils exhibit different chemical compositions and variations in their properties.

A1.2.3 *Advantages:*
A1.2.3.1 Available in a wide range of viscosity grades.
A1.2.3.2 Excellent lubricity.
A1.2.3.3 Additives can improve performance (antioxidants, corrosion protection, antiwear and EP properties, and so forth).
A1.2.3.4 Most sealing materials are compatible (little swelling or shrinking).
A1.2.3.5 Most paints are compatible.
A1.2.3.6 Cost-effective.

A1.2.4 *Disadvantages:*
A1.2.4.1 These oils age and oxidize at temperatures above approximately 100°C and form resins, carbonaceous deposits, and so forth.
A1.2.4.2 Viscosity index is lower than that of most synthetic fluids (that is, viscosity changes more rapidly with temperature).
A1.2.4.3 Oils used in instrument bearings have a relatively high vapor pressure.
A1.2.4.4 Not miscible with silicones and perfluoropolyethers.
A1.2.4.5 Usually are not preferred in applications where temperatures lie outside of the range from -30 to 100°C.[8]

A1.3 Polyalphaolefins (PAOs)

A1.3.1 *Use*—The PAOs are used to lubricate rolling element bearings in guidance systems, gimbals, gyros, and so forth. The PAOs are used as a base oil for PREB lubricants, especially for wide temperature and high-speed applications.

A1.3.2 *Structure*—PAOs, that is, synthetic paraffinic fluids, are primarily straight chain, saturated hydrocarbons. The PAOs differ in chain length, the degree of branching and in the position of the branches. The absence of unsaturation increases their thermo-oxidative stability.

A1.3.3 *Advantages:*
A1.3.3.1 Available in a wide range of viscosity grades.
A1.3.3.2 High thermal and oxidative stability.
A1.3.3.3 Low evaporation rates.
A1.3.3.4 Excellent viscosity-temperature behavior.
A1.3.3.5 Resistant against hydrolysis.
A1.3.3.6 High viscosity grades are compatible with most sealing materials and paints.
A1.3.3.7 Fully miscible with mineral oils and esters.
A1.3.3.8 A full range of additives are available.

A1.3.4 *Disadvantages:*
A1.3.4.1 Low viscosity grades may shrink/swell sealing materials.
A1.3.4.2 Not miscible with silicones and perfluoropolyethers.
A1.3.4.3 More costly than mineral oils.

A1.4 Esters

A1.4.1 *Use*—These fluids are used for lubrication of PREB. They serve as a base oil for low-temperature and high-speed lubricants.

A1.4.2 *Structure*—Diesters are esters usually based on lower molecular weight branched-chain alcohols reacted with C_4 to C_{10} aliphatic acids (usually forming azelates and sebacates). The polyolesters are synthesized from the alcohols trimethyl propane (TMP) or pentaerythritol and C_4 to C_8 acids.

A1.4.3 *Advantages:*
A1.4.3.1 Excellent low-temperature characteristics.
A1.4.3.2 Suitable for high-temperature applications up to 150°C.
A1.4.3.3 Excellent lubricity.
A1.4.3.4 Able to dissolve a wide concentration range of most additives.
A1.4.3.5 Low evaporation rates for some diesters and most polyol esters.
A1.4.3.6 High thermal and oxidative stability.
A1.4.3.7 Miscible with mineral oils, polyalphaolefins, and polyphenylmethylsilicones.

A1.4.4 *Disadvantages:*
A1.4.4.1 Only available in low to medium viscosity grades.
A1.4.4.2 Incompatible with some sealing materials such as BUNA-N, NBR, and EPDM elastomers.
A1.4.4.3 May interact with paint and other polymeric coatings.
A1.4.4.4 Can hydrolyze under humid conditions that may cause corrosion.
A1.4.4.5 Not miscible with polydimethylsilicones and perfluoropolyethers.
A1.4.4.6 More costly than mineral oils.

---

[8] This temperature limit is only a general guideline. Individual mineral oils may perform at temperature limits significantly different from this.

A1.5 Silicones

A1.5.1 *Use*—Silicones are used as lubricants for extremely low temperature (down to -75°C) applications. They may also be used for high temperature (up to 220°C) applications under light loads.

A1.5.2 *Structure*—There are three classes:

A1.5.2.1 Polydimethylsilicones have a linear chain structure with methyl groups.

A1.5.2.2 Polyphenylmethylsilicones (siloxanes) have a linear chain structure with methyl and phenyl groups. Siloxanes with a high ratio of phenyl to methyl groups show a decrease in evaporation and low temperature properties over that exhibited by the polydimethylsilicones. Siloxanes also show an improvement in thermal and oxidative stability and in surface tension properties.

A1.5.2.3 Fluorinated silicones have a branched structure based on perfluoroalkyl groups. Fluids having a branched chain structure exhibit better load-carrying capacity.

A1.5.3 *Advantages:*

A1.5.3.1 Available in a wide viscosity range.

A1.5.3.2 Polydimethylsilicones along with the linear perfluoropolyethers exhibit the best viscosity-temperature behavior of all lubricating oils.

A1.5.3.3 Excellent low temperature properties.

A1.5.3.4 Low evaporation rates.

A1.5.3.5 Compatible with almost all plastics and sealing materials with the exception of those based on silicones.

A1.5.3.6 Good damping properties.

A1.5.4 *Disadvantages:*

A1.5.4.1 Low surface tension (high tendency to spread and creep with the exception of the polyphenylmethylsilicones).

A1.5.4.2 Very poor lubricity.

A1.5.4.3 Can polymerize to glassy materials at elevated temperatures and under medium to heavy loads.

A1.5.4.4 Not miscible with mineral oils, polyalphaolefins, esters, and perfluoropolyethers.

A1.5.4.5 Difficult to remove by solvents.

A1.5.4.6 Can decompose in electrical arcs (electrical contacts) forming abrasive deposits.

A1.6 Perfluorolpolyethers (Perfluorinated Aliphatic Ethers) (acronyms–PFPE, PFAE)

A1.6.1 *Use*—These fluids are used as the base oil for high-temperature and oxygen-resistant lubricants. Both linear and branched-chain perfluoropolyethers are available. The linear PFPEs are primarily used for vacuum and space applications or where use at very low temperatures is required.

A1.6.2 *Structure*—These materials are long chain polyethers containing fully fluorinated alkyl groups. The fluorocarbon subunits may have a linear or branched-chain structure or a mixture of these two subunits.

A1.6.3 *Advantages:*

A1.6.3.1 Extraordinary high thermal and oxidative resistance.

A1.6.3.2 High resistance to chemical attack.

A1.6.3.3 Wide operating temperature range.

A1.6.3.4 Very low vapor pressure and evaporation rate; PFPEs with a linear structure have a significantly lower vapor pressures than their branched-chain counterparts.

A1.6.3.5 Medium to excellent viscosity-temperature behavior (linear structure–excellent, branched structure–medium).

A1.6.3.6 Compatible with sealing materials, plastics, and paints.

A1.6.4 *Disadvantages:*

A1.6.4.1 Low surface tension (spreading, creeping).

A1.6.4.2 Common lubricant additives are not soluble in these materials.

A1.6.4.3 Poor corrosion protection.

A1.6.4.4 Not suitable for aluminum, magnesium, and titanium alloys.

A1.6.4.5 Not miscible with other base stocks: mineral oils, esters, PAOs, silicones, and so forth.

A1.6.4.6 High density (approximately 1.9 g/mL).

A1.6.4.7 Poor boundary lubrication properties.

A1.6.4.8 May cause insulating films at electrical contacts.

A1.6.4.9 Can deposit monolayer films of PFPE species that are difficult to remove by solvents. The monolayer films will make bearing surfaces unwettable.

A1.6.4.10 High cost, especially for linear PFPEs.

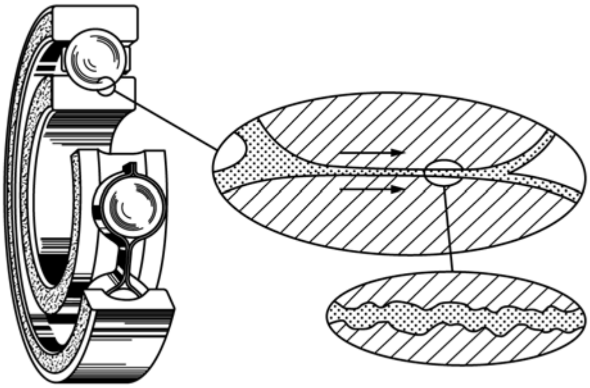
APPENDIX

X1. DISCUSSION OF ELASTOHYDRODYNAMIC LUBRICATION

X1.1 The life of miniature and small-size rolling element bearings is controlled by wear processes. In addition to the wear processes, larger bearings sizes may also undergo fatigue processes. To prevent or at least to reduce wear and damage to the surfaces of the bearing elements and to prolong the lifetime of rolling element bearings, a separation of the mating surfaces by means of a lubricating film of a sufficient thickness is necessary.

X1.2 The EHD theory is concerned with the thickness of the lubricating film built up between the rolling elements of a rolling element bearing (it can also be used for highly loaded gears and cams). The thickness of the lubricating film depends on the elastic deformation (Fig. X1.1) of the rolling element materials (steel or hybrid bearing), the bearing size, speed, the lubricant's operating viscosity, and on the lubricant quantity.

X1.3 The lubricant quantity rules the supply to the inlet zone of the contact and therefore has a direct effect on the film formation in the EHD contact zone. Depending on the lubricant supply and the resulting film thickness, EHD can be classified into three regimes: (*1*) parched EHD regime, (*2*) starved EHD regime, and (*3*) fully flooded EHD regime. The EHD theory was developed for oil lubrication but the principles can also be



NOTE 1—The vertical scale in the insets is magnified much more than the horizontal scale. Real surfaces do not have such high slopes.

FIG. X1.1 Schematic of EHD Film in a Ball Bearing

applied to grease lubrication.

X1.4 The lubricating film thickness between surfaces in rolling contacts according to the EHD theory can be calculated using Eq X1.1. The necessary parameters are shown in Fig. X1.2 for a line contact.

$$h_o = \frac{0.1\,\alpha^{0.6}}{(1/r_1 + 1/r_2)^{0.43}} \frac{(\eta\,\nu)^{0.7}}{(Q/l)^{0.13}} \frac{E}{(1-\mu^2)^{0.03}} \qquad (X1.1)$$

where:

h_o = minimum lubricating film thickness that will prevent roller/raceway contact (fully flooded EHD), µm

α = pressure-viscosity coefficient, α,

η = absolute (dynamic) viscosity, mPa-s,

ν = $(\nu_1 + \nu_2)/2$ speeds, m/s,

r_1 = roller radius, m,

r_2 = inner ring raceway radius, m,

Q = roller load, N,

l = roller length, m,

E = modulus of elasticity ($= 2.08 \times 10^{11}$ for steel), Pa, and

μ = Poisson's ratio (= 0.3 for steel).

The pressure-viscosity coefficient α for several lubricant fluids is listed in Table X1.1. The pressure-viscosity coefficient rises with an increase in viscosity.

X1.5 The EHD theory does not consider: (*1*) changes of the lubricant due to oxidation, and so forth, (*2*) extraordinary operating conditions (temperature, forces), and (*3*) environmental influences (fluids, atmosphere, vacuum, dust, and so forth).

X1.6 Please note that the EHD theory describes only the lubricating conditions within the rolling contact and not in the contacts where sliding is involved, for example, between the roller faces and lip surfaces of tapered roller faces and lip surfaces of tapered roller bearings. In such cases, the lubricating conditions are adequately described by the Hydrodynamic Theory.

X1.7 Eq X1.1 shows that the EHD film thickness primarily results from the rolling speed, *v*, the absolute viscosity, η, of the lubricating fluid (base oil of greases) at the operating temperature and atmospheric pressure, and from the pressure-viscosity coefficient, α (see Table X1.1).

X1.8 The Load, *Q*, has little influence because the viscosity rises with increasing loads and the contact surfaces are enlarged due to the elastic deformation of the steel roller elements (Fig. X1.2). This is, however, not the case with hybrid bearings, for example, with ceramic balls. The latter are hardly deformed elastically and do therefore not enlarge the contact area.

X1.9 Elastohydrodynamic Lubricating Regimes

X1.9.1 *Parched Regime*—This regime is characterized by very thin films that show changes in thickness during operation. Many instrument bearings operate under this condition. In this, mostly oil lubricated, system there is no free bulk lubricant. Lubrication is by a film so thin, by definition, that there is no flow outside the Hertzian contact under service acceleration. The oil flows in this regime only during Hertzian contact, and then only at right angles to the rolling direction, out of the contact. If it is not replaced the film continually thins.

X1.9.2 *Starved Regime*—Starved lubrication occurs if the contacts are not fully flooded. The lubricant supply is restricted but the system still contains free bulk lubricant. Starved lubrication is primarily used for grease lubricated high-speed rolling element bearings. In the single-charged starved grease contacts an initially high film thickness is followed by a substantial drop in the film thickness.

X1.9.3 *Fully Flooded Regime*—The lubricant is continuously supplied to the contact inlet in such a quantity that the inlet region is completely filled with the lubricant. The film thickness is in a steady state and the surfaces are completely separated by the lubricant film (Eq X1.1). The bearings reach the longest lifetime under fully flooded conditions.

X1.10 Extended Rating Life Calculation Based on the Ehd Theory for Bearings Operating at Higher Temperatures

X1.10.1 An estimate of bearing life is dependent upon the degree of separation expressed by the life adjustment factor a_{23} of the attainable fatigue life L_{na} (Eq X1.2 and Fig. X1.3) and by the ratio κ of the viscosity values at the operating temperature,

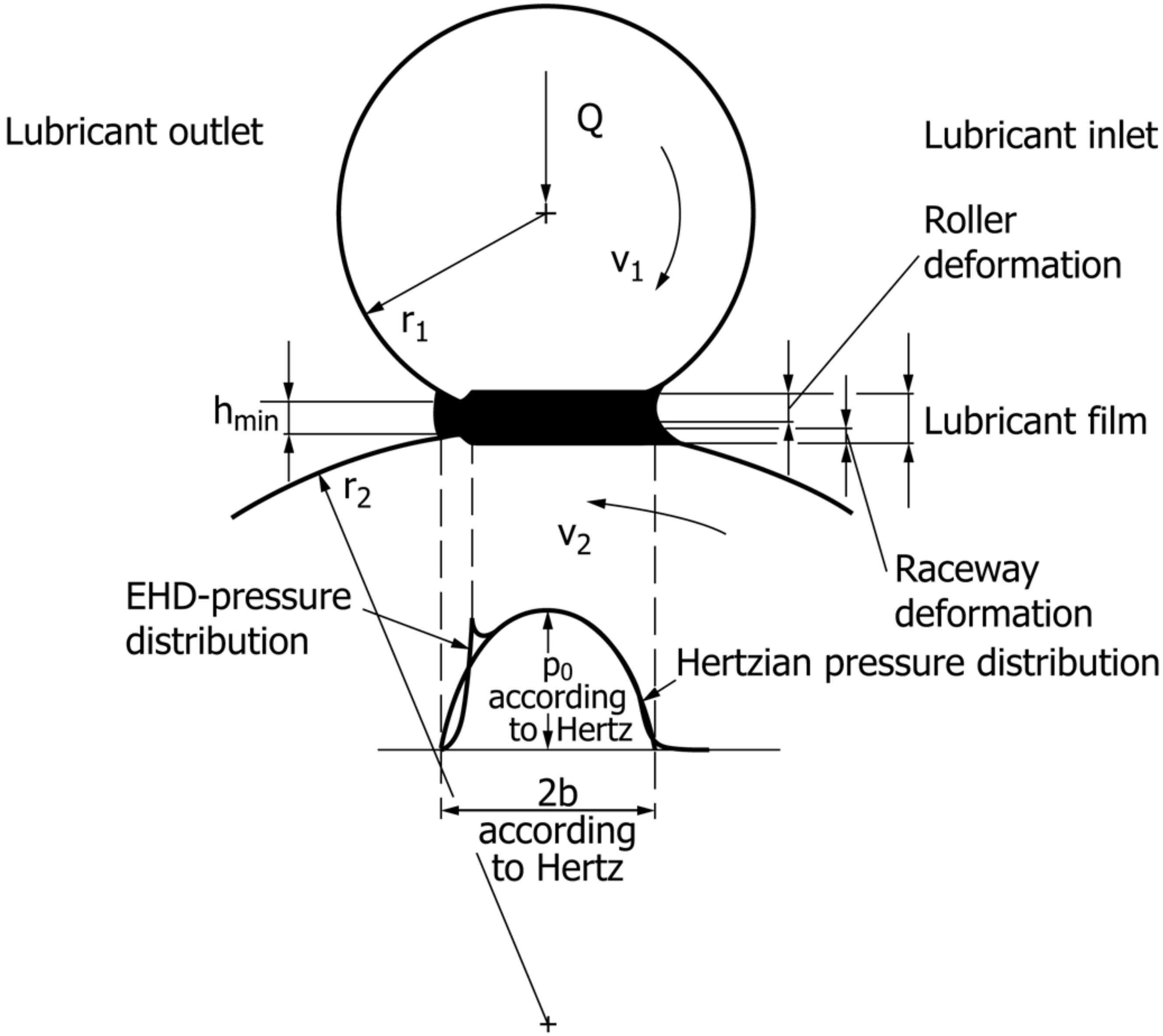


FIG. X1.2 Schematic of EHD Lubricating Film and Surface Deformation in a Roller/Inner Ring Contact

TABLE X1.1 Values of Different Lubricating Fluids at Room Temperature

Fluid	α-Value, GPa^{-1}
Mineral oil (paraffin-naphthenic)	21
Mineral oil (naphthenic-aromatic)	30
Polyalphaolefin	18
Diester (2-ethylhexyladipate)	7.6
Polyolester (pentaerythrittetravalerate)	7.5
Polydimethylsilicone	2.3
PFPE–straight	4–12
PFPE–branched	26–36

the so-called operating viscosity ν and the rated viscosity ν1, by *a*1, the life adjustment factor for failure probability, f_t , the temperature factor, and *L*, the rated life:

$$L_{na} = a_1 \cdot a_{23} \cdot f_t \cdot L \qquad \text{(X1.2)}$$

The rated viscosity, ν_1, can be assessed with the diagram in Fig. X1.4 by means of the mean bearing diameter d_m (millimetres) and the rotational speed (min^{-1}).

X1.10.2 The higher κ-values are reached when the contact areas between rolling elements and raceways are fully separated by the lubricating film and metal-to-metal contact does not occur (Zone I, κ < 4, Fig. X1.3). Under these ideal conditions of lubrication and with a very clean lubricant, the bearing life is primarily determined by the formation of pittings that have their origin in the areas of maximum materials stressing below the raceway surface. If the loads are moderate, which is frequently the case in practice, such bearings are fail-safe. This ideal condition cannot, however, be obtained at low speeds, high loads, and high temperatures, where the lubricating film is too thin to separate the surfaces sufficiently. This regime starts at κ < 4 and is strongly notable at κ < 0.4

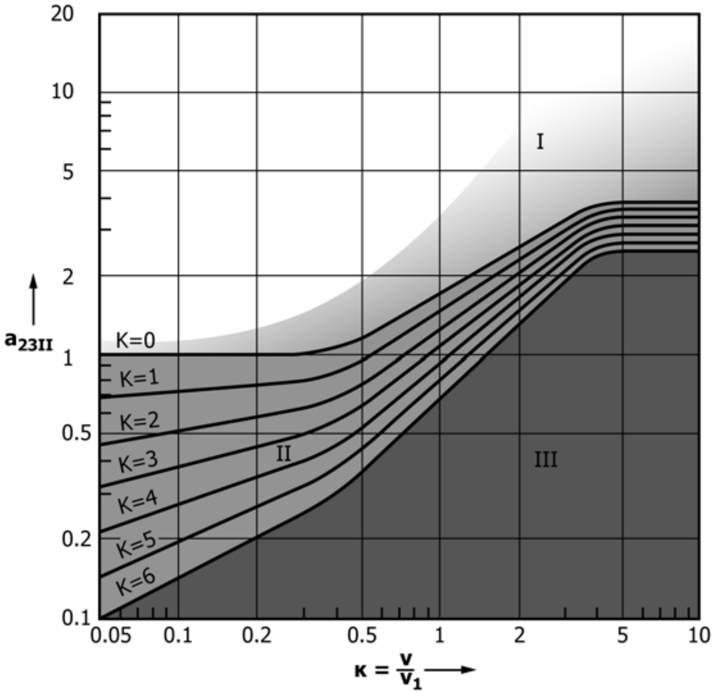


FIG. X1.3 Attainable Fatigue Life

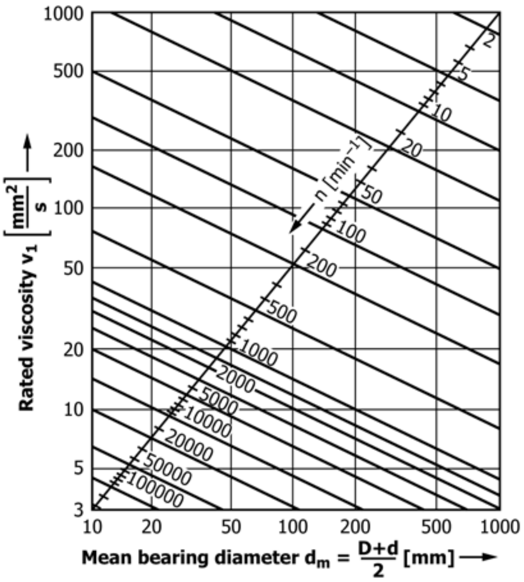


FIG. X1.4 Rated Viscosity, ν_1

(Zone II, Fig. X1.3). In this regime with decreasing κ-values, high wear can no longer be prevented. The lifetime of the bearing and the lubricant will be negatively influenced. Due to the increased metal-to-metal contacts, Zone II requires lubricants of high cleanliness and with adequate lubricating additives for wear reduction and increased load-carrying capacity (parched EHD and starved EHD regime). Zone III is the regime of unfavorable operating conditions, contaminated or unsuitable lubricants, or both.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; http://www.copyright.com/