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Standard Guide for
Monitoring Failure Mode Progression in Industrial Applications with Rolling Element Ball Type Bearings[1]

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INTRODUCTION

Oil analysis is a part of condition based maintenance programs. Despite being widely used for several decades, there is no systematic approach in selecting oil tests based on failure mode analysis. Most users select tests primarily based on oil degradation criteria, minimizing the potential for detecting surface damage and limiting the potential benefits of the oil analysis program. This guide provides justification for oil analysis in industrial applications from a failure standpoint to include both rolling element bearing wear and fluid deterioration.

1. Scope

1.1 This guide approaches oil analysis from a failure standpoint and includes both the rolling element ball type bearing wear and fluid deterioration in industrial application.

1.2 This guide pertains to improving equipment reliability, reducing maintenance costs and enhancing the condition-based maintenance program primarily for industrial machinery by applying analytical methodology to oil analysis program for the purpose of detecting specific failure modes.

1.3 This guide reinforces requirements for appropriate assembly, operation within the original design envelope as well as the need for condition-based and time-based maintenance.

1.4 This guide covers the principles of Failure Mode and Effect Analysis (FMEA) as described in Guide D7874 and its relationship to rolling element ball type bearing wear in industrial application and its fluid deterioration.

1.5 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D445 Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)

D664 Test Method for Acid Number of Petroleum Products by Potentiometric Titration

D1500 Test Method for ASTM Color of Petroleum Products (ASTM Color Scale)

D6304 Test Method for Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fischer Titration

D6595 Test Method for Determination of Wear Metals and Contaminants in Used Lubricating Oils or Used Hydraulic Fluids by Rotating Disc Electrode Atomic Emission Spectrometry

D7042 Test Method for Dynamic Viscosity and Density of Liquids by Stabinger Viscometer (and the Calculation of Kinematic Viscosity)

D7414 Test Method for Condition Monitoring of Oxidation in In-Service Petroleum and Hydrocarbon Based Lubricants by Trend Analysis Using Fourier Transform Infrared (FT-IR) Spectrometry

D7483 Test Method for Determination of Dynamic Viscosity and Derived Kinematic Viscosity of Liquids by Oscillating Piston Viscometer

D7596 Test Method for Automatic Particle Counting and Particle Shape Classification of Oils Using a Direct

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[1] This guide is under the jurisdiction of ASTM Committee D02 on Petroleum Products, Liquid Fuels, and Lubricants and is the direct responsibility of Subcommittee D02.96.04 on Guidelines for In-Services Lubricants Analysis.

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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.

Imaging Integrated Tester

D7685 Practice for In-Line, Full Flow, Inductive Sensor for Ferromagnetic and Non-ferromagnetic Wear Debris Determination and Diagnostics for Aero-Derivative and Aircraft Gas Turbine Engine Bearings

D7690 Practice for Microscopic Characterization of Particles from In-Service Lubricants by Analytical Ferrography

D7874 Guide for Applying Failure Mode and Effect Analysis (FMEA) to In-Service Lubricant Testing

2.2 *ISO Standards:*[3]

ISO 4407 Hydraulic Fluid Power—Fluid contamination—Determination of particulate contamination by the counting method using an optical microscope

ISO 11500 Hydraulic Fluid Power—Determination of the particulate contamination level of a liquid sample by automatic particle counting using the light-extinction principle

ISO 16232-7 Road Vehicles—Cleanliness of components of fluid circuits—Part 7: Particle sizing and counting by microscopic analysis

ISO 16700 Microbeam analysis—Scanning electron microscopy—Guidelines for calibrating image magnification

ISO 24597 Microbeam analysis—Scanning electron microscopy—Methods of evaluating image sharpness

3. Terminology

3.1 *Definitions:*

3.1.1 *bearing failure, n*—the termination of the bearing's ability to perform its design function.

3.1.2 *bearing failure initiation, n*—the moment a bearing starts to perform outside of its design function measured by performance characteristics.

3.1.3 *causes of failure, n*—underlying source(s) for each potential failure mode that can be identified and described by analytical testing.

3.1.4 *design function, n*—function or task that the system or components should perform.

3.1.5 *detection ability number [D], n*—ranking number that describes the ability of a specific fluid test to successfully detect a failure mode's cause or effects. A scale is used to grade detection ability numbers.

3.1.6 *dynamic viscosity [η], n*—ratio of applied shear stress and the resulting rate of shear.

3.1.6.1 *Discussion*—It is also sometimes called absolute viscosity. Dynamic viscosity is a measure of the resistance to flow of the liquid at a given temperature. In SI, the unit of dynamic viscosity is the Pascal·second (Pa·s), often conveniently expressed as milliPascal·second (mPa·s), which has the English system equivalent of the centipoise (cP).

3.1.7 *effects of failure, n*—potential outcome(s) of each failure mode on the system or component.

3.1.8 *elastohydrodynamic lubrication (EHD), n*—a condition where extremely high fluid interface pressure developed in concentrated rolling element contact causes the viscosity of the lubricant to increase by several orders of magnitude and for the surfaces to deform them appreciably in proportion to the thickness of a fluid film between the surfaces.

3.1.9 *failure-developing period (FDP), n*—period from component's incipient failure to functional failure.

3.1.10 *failure mode, n*—the physical description of the manner in which failure occurs.

3.1.11 *failure mode and effect analysis (FMEA), n*—analytical approach to determine and address methodically all possible system or component failure modes and their associated causes and effects on system performance.

3.1.11.1 *Discussion*—This approach can be used to evaluate design and track risk-reducing improvements to equipment reliability.

3.1.12 *hydrodynamic lubrication (HD), n*—lubrication regime where the load carrying surfaces are separated by a relatively thick film of lubricant formed by a combination of surface geometry, surface relative motion, and fluid viscosity.

3.1.13 *kinematic viscosity [v], n*—the ratio of the dynamic viscosity (η) to the density of the fluid (ρ).

3.1.13.1 *Discussion*—In SI, the unit of kinematic viscosity is m^2/s, often conveniently expressed as mm^2/s, which has the English system equivalent of the centistoke (cSt).

3.1.14 *severity number [S], n*—ranking number that describes the seriousness of the consequences of each failure's modes, causes and effects on potential injury, component or equipment damage, and system availability.

4. Summary of Guide

4.1 This guide is designed to assist users in the condition assessment of rolling element ball type bearing applications by selecting oil tests associated with specific failure modes, causes or effects for the purpose of detecting the earliest stage of failure development.

4.2 There are a number of different industrial systems with rolling element bearings. A simple horizontal bearing housing utilizing rolling element ball type bearings lubricated by oil splash will be discussed. This is a typical arrangement for many industrial overhang pump applications.

4.3 The focus of this guide is to select oil tests capable of detecting and monitoring progression of specific rolling element ball type bearing failure modes, their causes and effects as well as lubricating oil deterioration related to these failures.

5. Significance and Use

5.1 This guide is intended as a guideline for justification of oil test selection for monitoring rolling element ball type bearing conditions in industrial applications. Continuous benchmarking against similar applications is required to ensure lessons learned are continuously implemented.

5.2 Selection of oil tests for the purpose of detecting rolling element ball type bearing failure modes requires good understanding of equipment design, operating requirements and

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[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

surrounding conditions. Specifically, detailed knowledge is required on bearing design configuration, dimensional tolerances, load directions, design limitations, lubrication mechanisms, lubricant characteristics, and metallurgy of lubricated surfaces including bearing cages. Equipment criticality and accessibility as well as application of other monitoring techniques (for example, vibration, ultrasound or thermal images) are also critical information in this analysis process. In addition, detailed knowledge on the lubricating oil is paramount.

5.3 To properly apply the FMEA methodology users must understand the changes the system may encounter during all operating modes, their impact on design functions and available monitoring techniques capable of detecting these changes. To assist this approach, Section 6 will provide extensive descriptions on the rolling element ball type bearing failure modes, their causes and effects.

5.4 It is recognized that in most industrial applications vibration monitoring is the primary condition monitoring technique applied to detect failure modes, causes and effects in rolling element ball type bearings—while oil analysis is primarily used to monitor the lubricating oil properties. In the recent years, however, there is a trend toward using oil analysis in order to provide earlier detection of some failures of rolling element ball type bearings. This is particularly applicable to complex dynamic systems such as compressors, gearboxes and some gas turbines where obtaining vibration spectra and their analysis may be more difficult.

6. Failure Modes and Their Effects for Rolling Element Ball Type Bearing Applications

6.1 During normal operation, rolling element bearings operate primarily in the elastohydrodynamic (EHD) lubrication regime. However, in typical rolling element ball bearing application the lubrication between the rolling element and cage is usually controlled by the hydrodynamic (HD) lubrication principle.

6.2 The EHD oil film thickness depends on the elastic deformation of the rolling materials, bearing size, rolling speed, dynamic viscosity of the lubricating oil at operating temperature and pressure, as well as the pressure-viscosity coefficient.

6.3 The main failure modes of rolling element bearings are rapid or slow deterioration of the EHD film.

6.4 The rapid breakdown of EHD film can be caused by a sudden loss of lubricating oil available for splash lubrication, a rapid change in bearing operating conditions that is outside the original design basis, or accidental bearing material disintegration.

6.5 The slow deterioration of EHD oil film can be monitored by permanent sensors mounted on the bearing housing or by off-line, periodic oil sample analysis. Based on operating experience several causes are linked to this failure mode.

6.6 *Causes of Rolling Element Ball Type Bearing Failures:*

6.6.1 *Change in Dynamic Viscosity of the Lubricating Oil*—Although under the EHD theory dynamic viscosity value is reduced (approximately to the power 0.7), this oil property is still one of the main factors controlling the oil film thickness. In general, a reduction in dynamic viscosity will reduce oil film thickness. Under severe transient conditions, reduction of the oil film thickness may change the lubricating regime from EHD to mixed or boundary, resulting in an increased the risk of bearing surface contact and wear. Under the opposite condition when the dynamic viscosity is too high, an increase in drag and friction will result in local heat generation. This may increase the rate of chemical reaction within the oil film. In condition-based maintenance programs for industrial applications, kinematic viscosity at 40 °C (or occasionally at 100 °C) is used to measure this property. The assumption is that in most industrial applications, lubricant density is not significantly changed in the measured temperature of interest (for example, 40 °C or 100 °C) and trending kinematic viscosity can provide adequate prediction of the lubricant's ability to form a reliable and sustainable EHD oil film. However, newer methods exist that will measure dynamic viscosity directly (Test Method D7042). These methods may in time become commonly used in this approach.

6.6.2 *Deterioration of Lubricating Oil Chemistry*—The EHD lubrication condition will also depend on the complex relationship between properties of oil-to-metal adhesion and oil-to-oil cohesion. Applying a constant shear stress on the lubricating oil film may lead to physical damage to the lubricant molecules. The presence of atmospheric oxygen may initiate chemical reactions such as oxidation. High temperature and pressure will accelerate these reactions and cause thermal breakdown of lubricant molecules. Finally, lubricating oil will also deteriorate by the additive depletion process (for example, due to expected performance). The depletion rate would depend on the additive type, applications, and operating conditions. The consequences of these chemical changes will influence several critical properties such as cohesion, adhesion, surface tension, etc. Some visible changes might include an increase in foaming characteristics, air release, sludge and varnish formation, or reduced oil solubility characteristics.

6.6.3 *Increase in Gaseous, Liquid, and Solid Particle Contamination*—All three contaminant types will affect the EHD oil film but in different mechanisms.

6.6.3.1 An excessive amount of undissolved gas bubbles in the oil may weaken the load carrying capacity of the lubricating film. If the gas is reactive it can promote chemical degradation of the lubricant which may change the physical characteristics of the oil.

6.6.3.2 A large amount of liquid contaminants, particularly those having significantly different viscosity or density, may influence the dynamic viscosity. In addition, some contaminant may react with the lubricant affecting its performance characteristics. An example is free water, which may not support the external load acting on the bearing. It could also hydrolyze some of the additives, affecting their performance or cause rusting of bearing component.

6.6.3.3 The presence of solid particles is harmful in rolling element bearing applications due to significantly smaller oil film thickness and high interface pressure between rolling elements and raceway. Solid particles usually cause damage to rolling element surfaces by forming small indentations, which change the local surface fatigue leading to bearing failure.

6.6.4 *Abnormal Load in Contact Zones*—This can be caused by excessive thrust load, excessive internal preload, pinched outer ring, outer or inner ring misaligned.

6.6.4.1 Excessive thrust load may occur when there is axial overload from the machine resulting in very high stress which can cause metal fatigue.

6.6.4.2 Excessive internal preload may occur when there is no internal clearance in mounting bearing resulting in wider contact in the stationary ring.

6.6.4.3 A pinched outer ring occurs when outer ring has been forced out-of-run during installation resulting in rolling elements making contact with the outer ring raceway in more than one load zone. This may distort the housing which in turn will pinch the outer ring.

6.6.4.4 The outer ring is misaligned when it is not perpendicular to the centerline of the shaft. As a result, the outer ring could be cocked out of alignment and may result in premature bearing failure.

6.6.4.5 The inner ring misalignment may force the rolling elements making contacts with both the inner and outer ring raceways in a diagonal pattern on the sides of the raceways. This causes very high stress which can result in metal fatigue and premature bearing failure.

6.6.4.6 If the radial and axial loading of the ball bearing is too light, this can lead to ball smearing.

6.6.5 *Defective Bearing Seat on Shaft*—This condition occurs when the inner ring does not have a sufficient press fit on a shaft allowing slight movement of low amplitude resulting in fretting corrosion.

6.6.6 *Defective Bearing Seat in Housing*—This condition occurs when the bearing outside diameter and the housing bore do not make intimate contact allowing slight movements of low amplitude. This will result in fretting corrosion forming a reddish brown-black oxide and significant discoloration of lubricating oil. If the bearing seat is too tight this condition can cause overloading.

6.6.7 *Improper Mounting*—There are several conditions resulting from improper mounting causing premature bearing failures. These may include indentation at the top side of the ball groove, spalled or fractured outer ring, scoring on the inner ring raceway, misalignment, etc. All of these occurred during bearing installation and will have significant impact on bearing performance and life.

6.6.8 *Manufacturing Defects*—Due to significant improvement in the rolling element ball bearing manufacturing process, defects related to manufacturing processes have significantly been minimized. However, this cause cannot be completely eliminated from the root cause analysis although a typical oil condition monitoring program is not the best approach to detect this cause.

6.7 *Effects of Rolling Element Ball Type Bearing Failures:*

6.7.1 In addition to the presented different failure modes and causes, there are several failure effects of rolling element ball type bearings.

6.7.2 In technical literature there are several different classifications of ball bearing wear mechanisms. For the purpose of this guide, Table 1 presents a simplified wear classification of rolling element ball type bearings, which will be discussed in this guide.

6.7.3 *Bearing Surface Damage due to Subsurface Fatigue*—Subsurface fatigue is a form of wear that occurs after many cycles of high-stress flexing of the metal. This causes cracks in the subsurface of the metal, which then propagate to the surface, resulting in a piece of surface metal being removed or delaminated. It begins with inclusions or faults in the bearing metal below the surface. Solid particles in the EHD oil film which produce dents on the raceway may also initiate fatigue damage for bearings in motion. These round-bottomed dents often have a raised berm around their edges. The raised berm of metal generates stress concentrations below the load carrying surface, which after time causes crack. As the rolling elements pass over the cracks, fragments of material break away and this is known as flaking or spalling.

6.7.4 *Bearing Surface Damage due to Surface Stress*—If the lubricating film between raceway and the rolling elements become too thin, the peaks of the surface asperities will come in contact and cause small cracks, which are usually microscopic. They may, however, in severe conditions hasten the formation of sub-surface fatigue cracks and thus shortening the life of the bearing.

6.7.5 *Bearing Surface Damage due to Abrasive Wear*—This wear is estimated to be one of the most common sources of bearing wear. A roughened surface can cause cutting and damage to a mating surface that is in relative motion. Particle contamination can also cause similar damage. For example three-body abrasion occurs when a relatively hard contaminant of roughly the same size as the oil film thickness becomes imbedded in one metal surface (for example cage) and squeezed between the two surfaces. When the particle size is greater than the fluid film thickness, scratching, ploughing or gouging can occur. This creates parallel furrows in the direction of motion, like rough sanding. Mild abrasion by fine particles may cause polishing with a satiny, matte, or lapped-in appearance.

TABLE 1 Wear Classification of Rolling Element Ball Type Bearings

Failure Mode Effects of Rolling Element Bearings	
Wear Classification	Effects
Fatigue	Subsurface fatigue Surface distress
Wear	Abrasive Adhesive
Plastic Deformation	Overload Indentation
Corrosion	Moisture Fretting corrosion False Brinelling
Electric erosion	Craters Fluting
Fracture and cracking	Ring Cage