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Standard Guide for Monitoring Failure Mode Progression in Plain Bearings[1]

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INTRODUCTION

Oil analysis is a part of condition-based maintenance programs. Despite the wide use for several decades, there is no systematic approach to 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 an example of justification for oil analysis from a failure standpoint to include both component wear and fluid deterioration.

1. Scope*

1.1 This guide covers an oil test selection process for plain bearing applications by applying the principles of Failure Mode and Effect Analysis (FMEA) as described in Guide D7874.

1.2 This guide approaches oil analysis from a failure standpoint and includes both the bearing wear and fluid deterioration.

1.3 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 an oil analysis program for the purpose of determining the detection capability of specific failure modes.

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

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *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.*

1.7 *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]

D130 Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test

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

D665 Test Method for Rust-Preventing Characteristics of Inhibited Mineral Oil in the Presence of Water

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

D5185 Test Method for Multielement Determination of Used and Unused Lubricating Oils and Base Oils by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES)

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

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

[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.

*A Summary of Changes section appears at the end of this standard

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
D8112 Guide for Obtaining In-Service Samples of Turbine Operation Related Lubricating Fluid

2.2 *Other Documents:*[3]

ISO 4407 Hydraulic Fluid Power—Fluid Contamination—Determination of Particulate
ISO 11500 Hydraulic Fluid Power—Determination of the Particulate Contamination Level of a Liquid Sample by Automatic Particle Counting Using the Light-extinction Principle

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 *cause(s) 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.

3.1.5.1 *Discussion*—A scale is used to grade detection ability numbers.

3.1.6 *dynamic viscosity (η), n*—the ratio of applied shear stress and the resulting rate of shear of a liquid.

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 cgs system equivalent of the centipoise (cP).

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

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

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

3.1.10 *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 *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.

3.1.12 *kinematic viscosity (ν), n*—the ratio of the dynamic viscosity (η) to the density (ρ) of a fluid.

3.1.12.1 *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).

3.1.13 *occurrence number, O, n*—ranking number that describes the probability of occurrence of a failure mode's causes and effects over a predetermined period of time based on past operating experience in similar applications.

3.1.14 *P-F interval, n*—period from the point in time in which a change in performance characteristics or condition can first be detected (P) to the point in time in which functional failure (F) will occur.

3.1.15 *risk priority number, RPN, n*—a numeric assessment of risk assigned to FMEA process quantifying failure occurrence, severity of impact, and likelihood detection.

3.1.16 *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.

3.1.17 *white metal bearing alloys, n*—Metal alloys typically consisting of lead (Pb), tin (Sn) or zinc (Zn) with antimony (Sb) (some known as Babbitt) that are applied as a relatively thin surface to hydrodynamic bearings.

3.1.17.1 *Discussion*—These relatively soft materials are used to ensure embeddability of hard particle contaminants entrained in the lubricant and to ensure journal protection should oil supply be interrupted.

4. Summary of Guide

4.1 This guide assists users in the condition assessment of plain 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 plain bearings. For the purpose of demonstrating the applications of this methodology, a simple horizontal bearing housing utilizing a journal type plain bearing lubricated by an oil ring will be discussed. This example is a typical application for many industrial pumps and motors (**1**).[4]

4.3 The focus of this example is to select oil tests capable of detecting and monitoring the progression of specific plain bearing failure modes, their causes and effects, as well as lubricating oil deterioration.

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

[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

4.4 The expectation is that similar approaches will be applied to other system components lubricated under hydrodynamic condition to detect their specific failure modes.

5. Significance and Use

5.1 This standard is intended as a guideline for the justification of oil test selection for monitoring plain bearing conditions. One should employ a continuous benchmarking against similar applications to ensure lessons learned are continuously being implemented.

5.2 Selection of oil tests for the purpose of detecting plain bearing failure modes requires good understanding of equipment design, operating requirements, and surrounding conditions. Specifically, detailed knowledge is required of bearing design configuration, dimensional tolerances, load directions, design limitations, lubrication mechanisms, lubricant characteristics, and metallurgy of lubricated surfaces. 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 of the lubricating oil is paramount.

5.3 To properly apply the FMEA methodology, users must understand the changes encountered in the system during all operating modes, their impact on design functions, and available monitoring techniques capable of detecting these changes. To demonstrate this approach, Section 6 will provide extensive descriptions of the plain bearing failure modes, their causes, and effects.

6. Failure Modes and their Effects for Plain Bearing Applications

6.1 During steady state operation, plain bearings operate primarily under the hydrodynamic (HD) lubrication regime.

6.2 The main failure modes of plain bearings include rapid breakdown or slow deterioration of the HD oil film.

6.3 The rapid breakdown of HD oil film can be caused by a sudden loss of lubricating oil, rapid change in bearing operating conditions being outside the original design basis, or accidental bearing material disintegration. Wear sensors and other monitoring techniques (for example, bearing surface temperature or vibration sensors) would provide better monitoring capability for this failure mode.

6.4 The slow deterioration of HD oil film can be monitored by in-line oil sensors or off-line oil sample analysis. Based on operating experience, several causes are linked to this failure mode.

6.5 *Causes of Plain Bearing Failures:*

6.5.1 *Change in Dynamic Viscosity of the Lubricating Oil*—Dynamic viscosity at operating temperature is the only property representing the lubricant in the HD oil film thickness calculation. In general, reduction in dynamic viscosity will reduce the oil film thickness. Under severe transient conditions reduction of the oil film thickness may change the HD lubrication condition to a mixed lubrication regime and increase the risk of bearing surface contact and wear. If not corrected, it will cause bearing failure. In opposite conditions when the dynamic viscosity is too high, an increase in drag and friction will result in local heat generation, which may increase the rate of chemical reaction within the oil film. In condition-based maintenance programs, 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 HD oil film. Newer methods exist or are being developed that will measure dynamic viscosity directly (for example, Test Method D7042). These methods may in time become commonly used in this application.

6.5.2 *Deterioration of Lubricating Oil Chemistry*—The HD lubrication 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 lubricant molecules thermal breakdown. 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 will include an increase in foaming characteristics, air release, sludge and varnish formation, or reduce oil solubility characteristics.

6.5.3 *Increase in Gaseous, Liquid, and Solid Particle Contamination*—All three contaminants types will affect the HD oil film but in different mechanisms.

6.5.3.1 An excessive amount of undissolved gas bubbles in the oil weakens 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.

6.5.3.2 A large amount of liquid contaminants, particularly those having significantly different viscosity or density, may influence the dynamic viscosity. If this liquid has chemical reactivity with the lubricant, it could affect 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.

6.5.3.3 The presence of a moderate concentration of small solid particle contamination is of less concern in HD lubrication, assuming the particle sizes are smaller than the oil film thickness. However, the presence of solid particles is more harmful in boundary and mixed lubrication conditions. The presence of solid particles may increase the risk of some particles being imbedded in soft bearing surfaces and generate abrasive wear to the mating hard surfaces. In applications with a hydrostatic lift system, large solid particles may scratch surfaces around oil grooves, reducing bearing capability to generate the required hydrostatic lift during start up or shut down operations.

6.5.4 *Change in Bearing Surface Profile or Material Properties*—Changes in the relative speed of bearing surfaces or to the wedge profile will also influence the HD oil film. During start up or shut down operations, plain bearings most likely will operate for a short period under mixed or even boundary lubrication. At these conditions there is an increased risk of bearing surface contact resulting in surface wear, which may temper the profile of the lubricating oil wedge, thus affecting the oil film formation.

6.6 Typical corrective actions related to oil contamination include a total or partial replacement of the existing lubricating oil.

6.7 *Effects of Plain Bearing Failures* (**2**):

6.7.1 In general, five major types of wear are identified: adhesive, abrasive, fatigue, fretting and erosion. For the purpose of this guide, an extended version of the wear classification is proposed in Table 1.

6.7.2 *Bearing Surface Damage Due to Scoring and Wire Wool*—The term scoring is used to describe parallel or circumferential grooves on the bearing surface caused by dirt or debris presence between the bearing and mating surfaces. These particles can originate from wear of journal, bearing surfaces, system components, or from the surrounding environment. Small particles may also cause polishing of bearing surface that will have little effect on the bearing performance, providing the roughness and particle size do not exceed the thickness of the HD oil film. Large particles usually generate deep scores on the soft bearing surface or become embedded in the soft material generating scores on hard journal surface. Severe cases of damage to the mating surface can occur when shaft material contains chromium or manganese. Large embedded particles (approximately 1 mm) containing chromium or manganese in excess of 1 % may form a hard deposit of material by reaction with the steel journal. This mechanism is self-propagating when started and is usually referred to as "wire wool" damage. (**2**)

6.7.3 *Bearing Surface Damage Due to Wiping*—Bearing materials are normally chosen for their ability to conform to the mating surface. Therefore a slight wipe near one edge of the bearing indicates that the bearing surface layers melt and wipe in order to accept a particular configuration. Severe wipes lead to a new film thickness profile. Some associated problems with tighter clearances may occur during rapid start up of a cold machine, where the heat generated within the oil film may cause the shaft temperature to rise more rapidly than the bearing housing. Differential expansion of the shaft can cause a temporary reduction in bearing clearance, which in severe cases may cause metal-to-metal contact in the zone of minimum clearance. (**2**)

TABLE 1 Wear Classification of Plain Bearings with Failure Mode Effects for Plain Bearing Application

Wear Classification	Failure Mode Effects
Abrasive and adhesive wear	Scoring
	Wire wool
	Wiping
Fatigue	Cracking
Erosion	Groove formation
Fretting	Pivot Damage
Chemical	Corrosion
Electrical	Electrolysis (pitting)
	Rotating Magnetism
Thermal	Overheating/varnish
	Anisotropy
Metallurgical	Hydrogen blistering
	Tin migration
	Delamination

6.7.4 *Bearing Surface Damage Due to Cracking*—Cracking occurs when dynamic loads exceed temperature dependent white metal bearing alloy strength and is generally attributed to fatigue. A characteristic of fatigue damage is that the cracks may reach areas near the bond but they will then propagate through the white metal bearing alloy, leaving a portion of this alloy still adhering to the backing. The remaining white metal bearing alloy is often polished by the loose particles over a period of time. The fatigue strength of white metal bearing alloys decreases with increased temperature. Partial loss of oil supply may result in overheating and produce fatigue damage. Intergranular cracking is another form of fatigue mechanism and may be caused by a short period of overheating. The high temperature zone extends deeper than the surface layer of a single wipe so that more of the white metal bearing alloy is weakened. Frictional forces on the surface from contact with the shaft may cause partial shearing of the white metal bearing alloy opening up the cracks. This type of damage often extends only about half way through the thickness of the lining, presumably because the lower layer has more strength, being cooled from the backing. In general, surface cracking causes high vibration. (**2**)

6.7.5 *Bearing Surface Damage Due to Erosion*—High velocity regions, particularly at bearing edges or around sudden changes in bearing steps, may cause bearing material removal parallel to lubricating oil flow. This will form "canyons" which may change lubricant flow pattern, reducing the local film thickness and oil load carrying capacity. This wear may be amplified by the presence of solid particles in the oil. Another cause of erosion in journal bearings is cavitation where the fluid pressure increases in the load zone of the bearing. No metal-to-metal contact is needed. In the cavitation process vapor bubbles in the fluid are formed in low-pressure regions and are collapsed (imploded) in the higher-pressure regions of the oil system. The implosion can be powerful enough to create holes or pits, even in hardened metal when the implosion occurs at the metal surface. (**2**)

6.7.6 *Bearing Surface Damage Due to Pitting*—In most cases, pits have a hemispherical form, uniformly distributed over the zone area and may also be found on the mating surface. One cause of pitting is the discharge of an electric current through the oil film, resulting in spark erosion. In such cases, the pits are clean and shiny. If the pits have a black deposit, the pitting is attributed to a different mechanism.

6.7.7 *Bearing Damage Initiated by Fretting on a Pivot*—The reddish-oxide is formed by fretting around the concentrated contact area at the pivot of pad bearings. It may be