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Standard Guide for Practical Lubricant Condition Data Trend Analysis[1]

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INTRODUCTION

This standard provides specific guidelines for trend analysis, as they are applied to condition monitoring of machinery. The main purpose of trend analysis is to learn how rapidly the machine and fluid are deteriorating. A significant change in trend is indicative of a developing failure. Intervention in the early stages of deterioration is much more cost effective than failure of the machine.

Maximum reliability of in-service machine components and fluids requires a program of condition monitoring to provide timely indications of performance and remaining usable life. To achieve these goals, a condition monitoring program should monitor the rate of progression of the failure by including sufficient tests to determine the rate of degradation, increase of contaminants, and quantity and identity of metal debris from corrosion or wear.

The condition monitoring process determines the presence of oil-related failure modes, allowing remedial maintenance to take place before failure and subsequently expensive equipment damage occurs. In order to diagnose and predict machinery and fluid condition, the rate of change of machine condition must be trended. Equipment maintainers expect conditionmonitoring information to clearly and consistently indicate machinery condition, that is, the rate-of-change of component damage over time and the risk of failure.

Trending utilizes a comparison of a condition parameter with time. For example, plots of a condition-related parameter as a function of time is used to determine when the parameter is likely to exceed a given limit. Forecasting the expected breakdown of a machine well in advance enables the operator to minimize the machine's downtime

1. Scope*

1.1 This guide covers practical techniques for condition data trend analysis.

1.2 The techniques may be utilized for all instrumentation that provides numerical test results. This guide is written specifically for data obtained from lubricant samples. Other data obtained and associated with the machine may also be used in determining the machine condition.

1.3 This guide provides a methodology for assessing changes in lubricant during service. For limits on a specific lubricant parameter used in different system types, users should refer to Practice D4378, Practice D6224, or other established industry criteria, such as from the OEM. Guide D7720 may be used to determine limits if unavailable through the other references given.

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

1.4 This guide does not address upper or lower control limits. These limits are provided by product manufacturers, defined in ASTM specifications, or both. The range between upper and lower control limits should be greater than the range within each test method's repeatability coefficient. See Practices D3244, D6299, and D6792 for more information about ensuring that process control limits do not violate statistical fundamentals.

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~~ safety, health, and ~~health~~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]

D3244 Practice for Utilization of Test Data to Determine Conformance with Specifications
D4057 Practice for Manual Sampling of Petroleum and Petroleum Products
D4175 Terminology Relating to Petroleum Products, Liquid Fuels, and Lubricants
D4177 Practice for Automatic Sampling of Petroleum and Petroleum Products
D4378 Practice for In-Service Monitoring of Mineral Turbine Oils for Steam, Gas, and Combined Cycle Turbines
D6224 Practice for In-Service Monitoring of Lubricating Oil for Auxiliary Power Plant Equipment
D6299 Practice for Applying Statistical Quality Assurance and Control Charting Techniques to Evaluate Analytical Measurement System Performance
D6792 Practice for Quality Management Systems in Petroleum Products, Liquid Fuels, and Lubricants Testing Laboratories
D7720 Guide for Statistically Evaluating Measurand Alarm Limits when Using Oil Analysis to Monitor Equipment and Oil for Fitness and Contamination
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
E2587 Practice for Use of Control Charts in Statistical Process Control

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms used in this standard, refer to Terminology D4175.

3.1.2 *sample population, n*—group of samples organized for statistical analysis.

3.1.3 *statistical analysis, n*—a structured trending and evaluation procedure in which statistics relate individual test results to specific equipment failure mode and statistics is used to define the interpretation criteria and alarm limits.

3.1.4 *statistical process control (SPC), n*—set of techniques for improving the quality of process output by reducing variability through the use of one or more mechanisms, control charts, for example. A corrective action strategy is used to bring the process back into a state of statistical control. **E2587**

3.1.5 *trend analysis, n*—monitoring of the level and rate of change over operating time of measured parameters.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *alarm, n*—a means of alerting the operator that a particular condition exists.

3.2.2 *alarm limit, n*—set-point threshold used to determine the status of the magnitude or trend of parametric condition data.

3.2.2.1 *Discussion*—

In OEM provided alarm limits individual measurements are interpreted singly. Most fluid and machine failure modes do not give

[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.

rise to symptoms identifiable by a single measurement parameter. Early positive identification of a fault generally requires the combination of multiple condition measurements into a unique fault signature. See Guide D7874.

3.2.2.2 *Discussion—*

Establishing proper alarm limits can be a valuable asset for interpretation of test results to reflect the equipment's operation. The level and trend alarms can assist the equipment maintainer with reliability control and improvement. With the trending approach established, the machine operator's next objective is to establish guidelines for limits or extremes to which the results may progress to before requiring maintenance actions to be taken. The calculation of alarm limits should initially be developed based ~~on the ideal conditions and limitations from a sample population of condition data, although in reality, ideal conditions are not often met.~~upon a review of a statistically acceptable population of pertinent data along with data associated with failures where available.

3.2.3 *condition indicator, n—*a condition indicator is a variable that is statistically associated with an equipment or lubricant failure modes whose value can be established by inclusion of one or more measurements. Development of a condition indicator involves considerable analysis of equipment test, maintenance and failure histories. Most condition monitoring and analysis systems are centered on the gathering, storage and display of raw test data and trends. Data interpretation generally involves the evaluation of limit exceedence and trend plots.

3.2.3.1 *Discussion—*

A condition indicator should be unambiguous in its indication of a problem. The minimum requirement is that a combination of condition measurements and equipment usage provides a reliable indication of a specific machine or lubricant problem without ambiguity. A condition indicator should be statistically well behaved. It should stay within defined bounds given by the variability of machine-to-machine performance and instrument reproducibility. It should also be sufficiently sensitive to trigger an early alarm and it should be monotonic in its variation. Reliable warning and alarm limits should be established and maintained.

3.2.4 *condition tests, n—*the requirement for an effective condition monitoring program is utilizing tests that indicate failure modes and in sufficient time to prevent them.

3.2.4.1 *Discussion—*

Although the concept of measuring parameters to determine running condition of a system seems simple, a great many additional variables must be considered to ensure reliable condition prediction. These include, but are not limited to, machine type, machine configuration, operational considerations, oil type, oil quantity, consumption rate, maintenance history, etc.

3.2.5 *dead oil sampling, n—*oil sample taken that is not representative of the circulating or system oil due to one of several reasons, including the fluid in the system is static, the sample is taken from a non-flowing zone, and the sample point or tube within the oil was not flushed to remove the stagnant oil in the tube.

3.2.5.1 *Discussion—*

Without a proper oil sample, oil analysis techniques are not useful. The most fundamental issue for any oil analysis program is sample quality. Oil samples must be taken using the appropriate procedure for the machinery in question. The sample must be taken from the most effective location on the machine, whether it is via an on-line sensor or a bottled sample.

3.2.5.2 *Discussion—*

Maintenance, operational events, and sampling location are major factors affecting sample representation and, thus, the test results. Sampling without regard to location or maintenance and operational activities causes a high level of data variability. High data variability results in poor data interpretation and loss of program benefits.

3.2.6 *lubricant condition monitoring, n—*field of technical activity in which selected physical parameters associated with an operating machine are periodically or continuously sensed, measured, and recorded for the interim purpose of reducing, analyzing, comparing, and displaying the data and information so obtained and for the ultimate purpose of using interim results to support decisions related to the operation and maintenance of the machine.

3.2.7 *machinery health, n—*qualitative expression of the operational status of a machine subcomponent, component, or entire machine, used to communicate maintenance and operational recommendations or requirements in order to continue operation, schedule maintenance, or take immediate maintenance action.

3.2.8 *optimum sample interval, n—~~optimum (standard) sample interval~~in predictive maintenance practice,* ~~is derived from failure profile data. It is a fraction of the time~~ the time interval between initiation of a critical failure mode and equipment failure.~~ In general, sample intervals should be short enough to provide at least two samples prior to failure. The interval is established for the shortest critical failure mode.~~

3.2.8.1 *Discussion—*
The sample interval should be based on the critical failure mode for which the interval between likely failures is shortest. In general, sample intervals should be short enough to provide at least two samples prior to failure (that is, one-third the expected interval between failures).

3.2.8.2 *Discussion—*
Sampling, maintenance, and oil additions ~~may~~might not be performed at the ~~precisely~~ specified intervals. The irregular intervals common to most equipment operations can have a profound effect on measurement data. In particular, ~~the concentration of wear metals, contaminants and additives is affected greatly by~~ oil additions and machine ~~usage. Consequently, both the level and rate-of-change of these parameters must be considered for proper condition assessment. It is critical to establish an optimum sample interval. The optimum sample interval for a machine can be defined as an interval short enough to provide at least two samples during the period between the start of an abnormal condition and the initiation of a critical failure mode. In practice, an engineer should determine or at least verify all sample intervals by analyses of the equipment and historical data.~~usage can have a substantial effect on the concentrations of wear metals, contaminants, and additives.

3.2.8.3 *Discussion—*
Other monitoring technologies, such as vibration analysis, capabilities of secondary programs and failure mode patterns can also be used to determine the oil sampling interval.

3.2.9 *prognostics, n—*forecast of the condition or remaining usable life of a machine, fluid, or component part.

3.2.9.1 *Discussion—*
Individuals performing data review should demonstrate competency through recognized certification programs.

3.2.10 *remaining usable life, n—*subjective estimate based upon observations or average estimates of similar items, components, or systems, or a combination thereof, of the number of remaining time that an item, component, or system is estimated to be able to function in accordance with its intended purpose before replacement.

~~3.1.11 *sample population, n—*group of samples organized for statistical analysis.~~

~~3.1.12 *statistical analysis, n—*a structured trending and evaluation procedure in which statistics relate individual test results to specific equipment failure mode and statistics is used to define the interpretation criteria and alarm limits.~~

~~3.1.13 *statistical process control (SPC), n—*set of techniques for improving the quality of process output by reducing variability through the use of one or more mechanisms, control charts, for example. A corrective action strategy is used to bring the process back into a state of statistical control (Practice E2587).~~

~~3.1.14 *trend analysis, n—*monitoring of the level and rate of change over operating time of measured parameters.~~

3.3 *Symbols:*

Avg	=	average
C	=	current sample
H	=	usage metric (for example, hours)
OI	=	time on-oil interval
P	=	previous sample
PP	=	predicted prior sample
SSI	=	standard sample interval
T	=	trend

4. Summary of Guide

4.1 This guide provides practical methods for the trend analysis of condition data in the dynamic machinery operating environment. Various trending techniques and formulae are presented with their associated benefits and limitations.

5. Significance and Use

5.1 This guide is intended to provide machinery maintenance and monitoring personnel with a guideline for performing trend analysis to aid in the interpretation of machinery condition data.

6. Interferences

6.1 Sampling, maintenance, filter, and oil changes are rarely performed at precise intervals. These irregular, opportunistic intervals have a profound effect on measurement data and interfere with trending techniques.

6.2 *Machinery Operation*—Operational intensity can impact how quickly a component wears and how rapidly a fault progresses (**1**).[3] A relevant indicator of machine usage must be included in any calculations. The selected usage indicator must reflect actual machine usage, that is, life consumed (for example, stop/start cycles, megawatt hours, hours of use, or fuel consumption).

6.3 *Maintenance Events*—Component, filter, and oil changes impact the monitoring of machine performance, wear debris, contamination ingress and fluid condition. Maintenance events should always occur *after* a sample is taken (or condition test is performed). All maintenance events should be documented and taken into account during condition data interpretation. In all cases, maintenance events, if not reported, will reduce trending reliability.

6.4 *Sampling Procedures*—Improper or poor sampling techniques can profoundly impact condition test data (see Practices D4057 and D4177). Taking a good oil sample is a critical part of data trending. The following should be considered for a proper sampling procedure:

6.4.1 *Sample Quality:*

6.4.1.1 The most fundamental issue for any oil analysis program is sample representativeness. While poor analytical practices or insufficient data integrity checks generate data that cannot be reliably interpreted, improper sampling practices generate inaccurate data which is often meaningless with respect to condition monitoring or fault diagnosis.

6.4.1.2 Sample bottles can have a considerable influence on test results, particularly on oil cleanliness results. In practice, only sample bottles qualified for cleanliness should be used. When samples are to be taken from ultra clean machinery such as industrial hydraulic systems, the sample bottle must be rated as ultra clean. Exposing the new bottle or cap to the atmosphere negates any cleanliness certification.

6.4.1.3 The primary objective of the oil sampling process is to acquire a representative sample, for example, one whose properties, contaminants, and wear metals accurately reflect the condition of oil and machine. Theoretically, a representative sample means the concentration and size distribution of particulates and chemical species in the sample bottle correlate with those in the oil reservoir. Data variability may result from sampling procedures, sampling locations, improper maintenance activities, operational events (for example, exposure to high stress or temperature variation), analytical testing, data entry, and presence of one or more conflicting failure modes.

6.4.2 A significant difference in the test data could trigger a false trend alarm. Examples of poor sampling techniques are:

6.4.2.1 Stagnant sampling,

6.4.2.2 Sampling after component change out,

6.4.2.3 Sampling after oil, or filter changes, or both,

6.4.2.4 Irregular sample intervals, and

6.4.2.5 Sampling intermittent or standby equipment without circulating the oil and bringing the equipment to operating temperatures.

6.5 *Laboratory and Testing Practices*—The tools used to perform the condition monitoring tests impact the data.

6.5.1 Analytical instrument differences impact data reliability. Trending should only be performed on results from the same make and model of test instrument. For example, trending atomic emission inductively coupled plasma (ICP) results should be from ICPs with the same sample introduction configuration, same plasma energy, and preferably, the same manufacturer and model of the ICP

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

instrument. Differences between testing laboratories always show the largest bias. The trend data should be generated by the same laboratory whenever possible. If a new laboratory is going to be used, overlapping test data should be performed. When multiple laboratories are utilized, a correlation between them should be established.

6.5.2 Analytical instruments with poor measurement repeatability and reproducibility will result in correspondingly poor trending. Testing repeatability should also be included with the trending studies.

6.5.3 Inappropriate analysis techniques can hide or distort interpretational conclusions. The condition-monitoring tool chosen must provide evidence of the critical failure modes under review.

6.6 *Machinery Wear Process*—Wear metal concentrations in oil are subject to variability (**2**).

6.6.1 Filters remove the majority of debris particles greater than filter pore size. Thus an oil sample only captures new wear and small, suspended, old wear.

6.6.2 Wear particle release is event driven; increased load or speed can result in increased wear.

6.6.3 The rate of wear debris release is not linear with time. For many fault mechanisms, wear occurs in bursts.

6.6.4 Wear metal analysis methods can have particle size limitations that should be included in the evaluations. For example, ICP metal analyses are limited to those particles below nominally 8 microns.

6.7 *Reservoir/Sump Volumes*—Fluid and wear condition parameters are concentration measurements and are affected by reservoir/sump size. Varying the oil volumes in a reservoir can impact the trending analysis. For example, infrequent top ups allows the oil volume to decrease and thus concentrate the wear debris and contaminants. Alternatively, large volumes of make-up oil dilute the concentrations. Small, routine oil top-ups reduce this interference. The fluid make-up rate should be considered as apart of the evaluation practice.

6.8 When trending for a specific piece of equipment, one should look at the difference between the current sample and an average of a group of previous samples from that piece of equipment or a group of samples from as many similar units as possible. Basing a trend on just two data points can leave significant room for error and misjudgment.

6.9 When samples cannot be taken in exact intervals, techniques should be applied that overcome these irregular intervals.

6.10 Effective data trending requires that the above interferences are taken into account. The effect of operation and maintenance activities must be tuned out for the most effective trending.

6.11 The data history under trend analysis must be from the machine component, and all samples must be contiguous.

6.12 *Qualified Data Review*—Individuals performing data review should demonstrate competency through recognized certification programs.

7. Procedure

7.1 *Preparing Condition Data for Analysis*—The first step in preparing condition data is to ensure all measurement data, for example iron (Fe) from AES, is generated from the same analytical instrument. Due to the proprietary techniques used by instrument manufacturers, few instruments provide the same results from the same sample unless the instrument is the same make and model and has the same calibration. When multiple instruments or laboratories are utilized, the instruments must be controlled in a data correlated program. A lack of these conditions will contribute to increased variance and less accurate trending.

7.2 *Trending Test Data:*

7.2.1 *Traditional Techniques*—There are numerous techniques to calculate trends from the very simple to the more complex. There are advantages and disadvantages to each method.

7.2.1.1 *Difference (Delta) Trend*—The difference trend between sequential samples is the current sample value minus the previous sample value.

$$T = C - P \quad (1)$$

The difference trend is easy to calculate, however it does not account for machine usage and is ineffective in determining the rate of wear or oil deterioration. This is the traditional "eyeball" method where gross changes, such as doubling since the last sample, are noted. This formula does not factor in the equipment duty cycle and is a poor indicator of machinery or fluid condition.

7.2.1.2 *Percent Change Trend*—The percent change trend is the current sample minus the previous sample, divided by the current sample value, times 100.

$$T = (C - P)/C \times 100 \quad (2)$$

The percent change since the last sample can be a better indication of trend but still does not account for equipment usage or duty cycle. In addition, this calculation provides ambiguous numbers for fractional data. For example, an increase from 0.1 to 1 is the same percent change as from 10 to 100. Percent change is only effective for large trend changes (for example trending intervals that yield *C* or *P* of 100) and only when the equipment is used continuously and rigorously sampled at a standard interval.

7.2.1.3 *Rise-Over-Run Trend*—The rise-over-run trend is the current sample minus the previous sample, divided by the usage metric, times the standard sample interval. The usage metric and the standard sample interval metric must be the same units of measure, for example, hours.

$$T = [(C - P)/H] \times SSI \quad (3)$$

The rise-over-run trend calculation, which factors in equipment usage, is shown in Fig. 1. The scheduled sample interval for this equipment is 150 hours. In this example, the trend could be for any contaminant, for instance, the removal of lead from the Babbitt overlay of a bearing. The plot also indicates the "Alert" and "Reportable" alarm limits. Rise over run trend can be effective for continuous duty and intermittent duty machinery. However, condition samples must be taken at or near the optimum interval. The optimum (standard) sample interval is derived from failure profile data. It is a fraction of the time between initiation of a critical failure mode and equipment failure. In general, sample intervals should be short enough to provide at least two samples prior to failure. The interval can be established for the shortest critical failure mode. Samples taken at very short or very long intervals relative to the standard interval generate ambiguous results due to the multiplication factor in the formula.

7.2.1.4 *Cumulative Trend*—The cumulative trend is the sum of previous and current sample.

$$T = \sum_n C \quad (4)$$

The cumulative trend plot provides a quick indication as to whether data points in a series are maintaining a linear trend slope or are beginning to deviate due to an anomaly. The cumulative trend plot is most effective when equipment is used continuously.

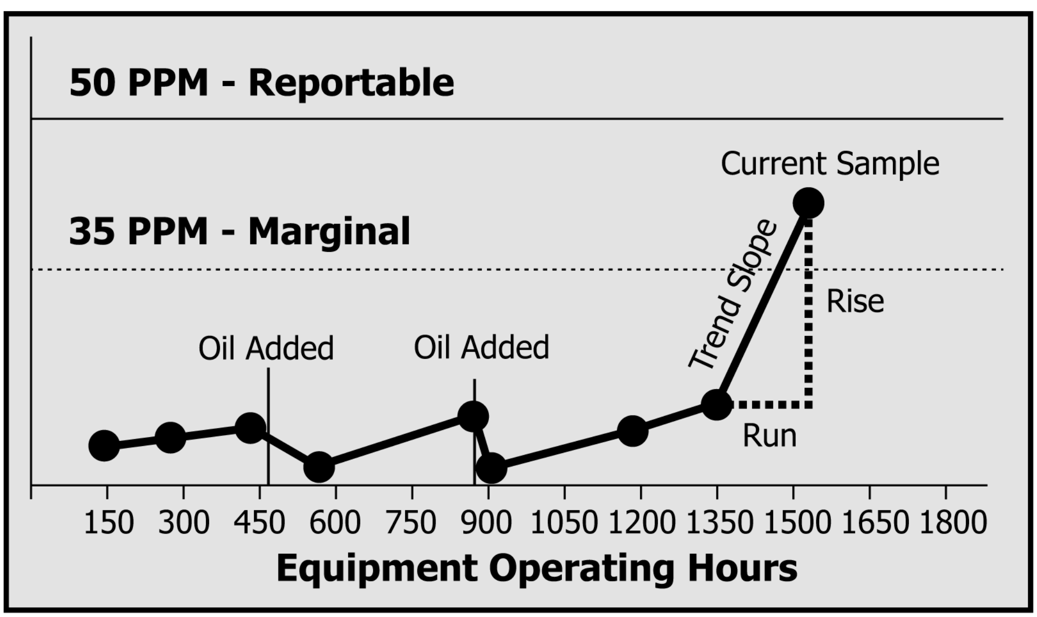

FIG. 1 Trend Plot Demonstrating Rise–Over–Run