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Standard Guide for Statistically Evaluating Measurand Alarm Limits when Using Oil Analysis to Monitor Equipment and Oil for Fitness and Contamination¹

This standard is issued under the fixed designation D7720; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This guide provides specific requirements to statistically evaluate measurand alarm thresholds, which are called alarm limits, as they are applied to data collected from in-service oil analysis. These alarm limits are typically used for condition monitoring to produce severity indications relating to states of machinery wear, oil quality, and system contamination. Alarm limits distinguish or separate various levels of alarm. Four levels are common and will be used in this guide, though three levels or five levels can also be used.

1.2 A basic statistical process control technique described herein is recommended to evaluate alarm limits when measurand data sets may be characterized as both parametric and in control. A frequency distribution for this kind of parametric data set fits a well-behaved two-tail normal distribution having a “bell” curve appearance. Statistical control limits are calculated using this technique. These control limits distinguish, at a chosen level of confidence, signal-to-noise ratio for an in-control data set from variation that has significant, assignable causes. The operator can use them to objectively create, evaluate, and adjust alarm limits.

1.3 A statistical cumulative distribution technique described herein is also recommended to create, evaluate, and adjust alarm limits. This particular technique employs a percent cumulative distribution of sorted data set values. The technique is based on an actual data set distribution and therefore is not dependent on a presumed statistical profile. The technique may be used when the data set is either parametric or nonparametric, and it may be used if a frequency distribution appears skewed or has only a single tail. Also, this technique may be used when the data set includes special cause variation in addition to common cause variation, although the technique should be repeated when a special cause changes significantly or is eliminated. Outputs of this technique are specific mea-

surand values corresponding to selected percentage levels in a cumulative distribution plot of the sorted data set. These percent-based measurand values are used to create, evaluate and adjust alarm limits.

1.4 This guide may be applied to sample data from testing of in-service lubricating oil samples collected from machinery (for example, diesel, pumps, gas turbines, industrial turbines, hydraulics) whether from large fleets or individual industrial applications.

1.5 This guide may also be applied to sample data from testing in-service oil samples collected from other equipment applications where monitoring for wear, oil condition, or system contamination are important. For example, it may be applied to data sets from oil filled transformer and circuit breaker applications.

1.6 Alarm limit evaluating techniques, which are not statistically based are not covered by this guide. Also, the techniques of this standard may be inconsistent with the following alarm limit selection techniques: “rate-of-change,” absolute alarming, multi-parameter alarming, and empirically derived alarm limits.

1.7 The techniques in this guide deliver outputs that may be compared with other alarm limit selection techniques. The techniques in this guide do not preclude or supersede limits that have been established and validated by an Original Equipment Manufacturer (OEM) or another responsible party.

1.8 *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.*

1.9 *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.*

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-Service Lubricants Analysis.

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

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
- D974** Test Method for Acid and Base Number by Color-Indicator Titration
- D2896** Test Method for Base Number of Petroleum Products by Potentiometric Perchloric Acid Titration
- D4175** Terminology Relating to Petroleum Products, Liquid Fuels, and Lubricants
- D4378** Practice for In-Service Monitoring of Mineral Turbine Oils for Steam, Gas, and Combined Cycle Turbines
- D4928** Test Method for Water in Crude Oils by Coulometric Karl Fischer Titration
- D5185** Test Method for Multielement Determination of Used and Unused Lubricating Oils and Base Oils by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES)
- 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
- D6304** Test Method for Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fischer Titration
- D6439** Guide for Cleaning, Flushing, and Purification of Steam, Gas, and Hydroelectric Turbine Lubrication Systems
- 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
- D6786** Test Method for Particle Count in Mineral Insulating Oil Using Automatic Optical Particle Counters
- D7042** Test Method for Dynamic Viscosity and Density of Liquids by Stabinger Viscometer (and the Calculation of Kinematic Viscosity)
- D7279** Test Method for Kinematic Viscosity of Transparent and Opaque Liquids by Automated Houillon Viscometer
- 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
- D7416** Practice for Analysis of In-Service Lubricants Using a Particular Five-Part (Dielectric Permittivity, Time-Resolved Dielectric Permittivity with Switching Magnetic Fields, Laser Particle Counter, Microscopic Debris Analysis, and Orbital Viscometer) Integrated Tester
- D7483** Test Method for Determination of Dynamic Viscosity

and Derived Kinematic Viscosity of Liquids by Oscillating Piston Viscometer

- D7484** Test Method for Evaluation of Automotive Engine Oils for Valve-Train Wear Performance in Cummins ISB Medium-Duty Diesel Engine
- D7596** Test Method for Automatic Particle Counting and Particle Shape Classification of Oils Using a Direct Imaging Integrated Tester
- D7647** Test Method for Automatic Particle Counting of Lubricating and Hydraulic Fluids Using Dilution Techniques to Eliminate the Contribution of Water and Interfering Soft Particles by Light Extinction
- D7670** Practice for Processing In-service Fluid Samples for Particulate Contamination Analysis Using Membrane Filters
- D7684** Guide for Microscopic Characterization of Particles from In-Service Lubricants
- 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
- E2412** Practice for Condition Monitoring of In-Service Lubricants by Trend Analysis Using Fourier Transform Infrared (FT-IR) Spectrometry

3. Terminology

3.1 *Definitions*:

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

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

3.1.3 *assignable cause, n*—factor that contributes to variation in a process or product output that is feasible to detect and identify; also called *special cause*.

3.1.4 *boundary lubrication, n*—condition in which the friction and wear between two surfaces in relative motion are determined by the properties of the surfaces and the properties of the contacting fluid, other than bulk viscosity.

3.1.4.1 *Discussion*—Metal to metal contact occurs and the chemistry of the system is involved. Physically adsorbed or chemically reacted soft films (usually very thin) support contact loads. Consequently, some wear is inevitable.

3.1.5 *chance cause, n*—source of inherent random variation in a process which is predictable within statistical limits; also called *common cause*.

3.1.6 *characteristic, n*—property of items in a sample or population which, when measured, counted or otherwise observed, helps to distinguish between the items.

3.1.7 *data set, n*—logical collection of data that supports a user function and could include one or more data tables, files, or sources.

3.1.7.1 *Discussion*—Herein a data set is a population of values for a measurand from within a particular measurand set and covering an equipment population.

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

3.1.8 *distribution, n*—as used in statistics, a set of all the various values that individual observations may have and the frequency of their occurrence in the sample or population.

3.1.9 *measurand, n*—particular quantity subject to measurement.

3.1.9.1 *Discussion*—In industrial maintenance a measurand is sometimes called an *analysis parameter*.

3.1.9.2 *Discussion*—Each measurand has a unit of measure and has a designation related to its characteristic measurement.

3.1.10 *nonparametric, n*—term referring to a statistical technique in which the probability distribution of the constituent in the population is unknown or is not restricted to be of a specified form.

3.1.11 *normal distribution, n*—frequency distribution characterized by a bell shaped curve and defined by two parameters: mean and standard deviation.

3.1.12 *outlying observation, n*—observation that appears to deviate markedly in value from other members of the sample set in which it appears, also called *outlier*.

3.1.13 *parametric, n*—term referring to a statistical technique that assumes the nature of the underlying frequency distribution is known.

3.1.14 *population, n*—well defined set (either finite or infinite) of elements.

Statistical Process Control Technique Terms

3.1.15 *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 control charts and a corrective action strategy used to bring the process back into a state of statistical control.

3.1.16 *state of statistical control, n*—process condition when only common causes are operating on the process.

3.1.17 *center line, n*—line on a control chart depicting the average level of the statistic being monitored.

3.1.18 *control limits, n*—limits on a control chart that are used as criteria for signaling the need for action or judging whether a set of data does or does not indicate a state of statistical control based on a prescribed degree of risk.

3.1.18.1 *Discussion*—For example, typical three-sigma limits carry a risk of 0.135 % of being out of control (on one side of the center line) when the process is actually in control and the statistic has a normal distribution.

3.1.19 *warning limits, n*—limits on a control chart that are two standard errors below and above the center line.

3.1.20 *upper control limit, n*—maximum value of the control chart statistic that indicates statistical control.

3.1.21 *lower control limit, n*—minimum value of the control chart statistic that indicates statistical control.

Cumulative Distribution Technique Terms

3.1.22 *cumulative distribution, n*—representation of the total fraction of the population, expressed as either mass-, volume-, area-, or number-based, that is greater than or less than discrete size values.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *alarm limit, n*—alarm condition values that delineate one alarm level from another within a measurand set; also called *alarm threshold*.

3.2.1.1 *Discussion*—When several alarm levels are designated, then a first alarm limit separates the normal level from the alert level, and a second alarm limit separates the alert level from action level. In other words, measurand data values greater than the first alarm limit and less-than-or-equal-to the second alarm limit are in the state of the second level alarm.

3.2.1.2 *Discussion*—An alarm limit, “X”, may be single-sided such as “greater than X” or “less than $-X$ ”; or it may be double-sided such as “greater than X and less than $-X$ ”. Alarm limit values may represent the same units and scale as the corresponding measurand data set, or they may be represented as a proportion such as a percent. Alarm limit values may be zero-based, or they may be relative to a non-zero reference or other baseline value.

3.2.1.3 *Discussion*—Statistical process control is used to evaluate alarm limits comparing a control limit value with an alarm limit value. Statistical cumulative distribution is used to evaluate alarm limits by identifying a cumulative percent values corresponding with each alarm limit value and comparing those results, for example, percentages of a data set in each alarm level, with expected percentages of the data set typically associated with each alarm level.

3.2.2 *alarm limit set, n*—collection of all the alarm limits (alarm condition threshold values) that are needed for an alarm-based analysis of measurands within a measurand set.

3.2.3 *critical equipment, n*—category for important production assets that are not redundant or high value or highly sensitivity or otherwise essential, also called *critical assets* or *critical machines*.

3.2.4 *equipment population, n*—well defined set of like equipment operating under similar conditions, selected and grouped for condition monitoring purposes; also called *machine population*, *asset population*, and *fleet*.

3.2.4.1 *Discussion*—Like equipment may refer to equipment of a particular type that may include make, model, lubricant in use, and lubrication system. Similar conditions may include environment, duty-cycle, loading conditions.

3.2.5 *measurand set, n*—meaningful assemblage of measurands collectively representing characteristic measurements that reveal modes and causes of failure within an equipment population.

3.2.5.1 *Discussion*—In industry, a measurand set is sometimes called an *analysis parameter set*.

3.2.6 *noncritical equipment, n*—category for production assets that are not critical equipment; also called *balance of plant*.

3.2.7 *optimum sample interval, n*—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 is established for the shortest critical failure mode.

Alarm Level Terms (in order of severity)

3.2.8 *WHITE, adj*—favorable level alarm designation showing undamaged or as-new condition having reasonable wear or expected operational condition.

3.2.8.1 *Discussion*—Some other terms used for this level of alarm may include but are not limited to normal, satisfactory, acceptable, level 1, level A, suitable for continued use and good.

3.2.8.2 *Discussion*—WHITE level alarm condition is not usually accentuated by any special color indication on displays or reports.

3.2.9 *GREEN, adj*—favorable alarm level designation showing acceptable condition and showing a measurable change in a measurand value compared with WHITE alarm level.

3.2.9.1 *Discussion*—Some other terms used for this level of alarm may include but are not limited to fair, watch list, monitor, acceptable, level 2, level B and moderate.

3.2.9.2 *Discussion*—GREEN level alarm condition is commonly accentuated by green letters or green highlight or green background in displays or reports.

3.2.10 *YELLOW, adj*—intermediate level alarm designation warning a fault condition is present and will likely need attention in the future.

3.2.10.1 *Discussion*—Some other terms used for this level of alarm may include but are not limited to amber, alert, level 3, level C, low action priority, caution, warning, and abnormal.

3.2.10.2 *Discussion*—YELLOW level alarm condition is commonly accentuated by yellow letters or yellow highlight or yellow background in displays or reports.

3.2.11 *RED, adj*—high level alarm designation showing significant deterioration, review other condition information and consider a possible intervention.

3.2.11.1 *Discussion*—Some other terms used for this level of alarm may include but are not limited to extreme, danger, level 4, level D, unsuitable, actionable, alarm and fault.

3.2.11.2 *Discussion*—RED alarm condition is commonly accentuated by red letters or red highlight or red background in displays or reports.

4. Summary of Guide

4.1 This guide is used to statistically evaluate and adjust alarm limits for condition monitoring based on representative measurand data sets from in-service oil sample testing and analysis. This statistical analysis should be performed periodically to update alarm levels using historical data available to the user.

4.2 The user defines an equipment population. The user then selects an appropriate measurand set representing characteristic measurements that reveal likely modes and causes of degradation or failure for the lubricated machinery and for the lubricants for that equipment population.

4.3 For each alarm based measurand the user must have a statistically representative data set covering the equipment population. If the data set follows a parametric statistical distribution, then the user may apply statistical process control (SPC) and cumulative distribution techniques to statistically

evaluate alarm limit values. If the data set is nonparametric or if it includes special cause variation, then the user may apply cumulative distribution technique to statistically evaluate and make practical adjustments to existing alarm limit values.

5. Significance and Use

5.1 Alarm limits are used extensively for condition monitoring using data from in-service lubricant sample test results. There are many bases for initially choosing values for these alarm limits. There are many questions that should be addressed. These include:

Are those limits right or wrong?

Are there too many false positive or false negative results?

Are they practical?

5.2 This guide teaches statistical techniques for evaluating whether alarm limits are meaningful and if they are reasonable for flagging problems requiring immediate or future action.

5.3 This guide is intended to increase the consistency, usefulness, and dependability of condition based action recommendations by providing machinery maintenance and monitoring personnel with a meaningful and practical way to evaluate alarm limits to aid the interpretation of monitoring machinery and oil condition as well as lubricant system contamination data.

6. Assumptions and Limitations

6.1 The assumptions below define the ideal conditions and limitations for alarm limits from a data set representing an equipment population. It is understood that ideal conditions are not often met and that actual conditions may impact the accuracy or sensitivity of the alarm limits. Assumption and conditions include:

6.1.1 Caution should be used for data sets with too few members.

6.1.1.1 For SPC techniques using a normal distribution, caution should be used for data sets with fewer than 30 members. Tentative limits can be set from as little as 10 samples although the quality of the limits will improve with larger populations. Larger populations (for example, in the hundreds) can provide best alarm limits. However, the data needs to be representative of the equipment population.

6.1.1.2 For cumulative distribution techniques regardless of the form of distribution, caution should be used for data sets with fewer than 100 members. Tentative limits can be set from as little as 50 samples although the quality of the limits will improve with larger populations. Larger populations (for example, 1000 plus) can provide best alarm limits. However the data needs to be representative of the equipment population.

6.1.2 The machinery process is a closed loop system whereby test measurements are only affected by operations, maintenance or the onset of a failure mode.

6.1.3 An equipment population or fleet is a population of like machines that would be expected to be maintained according to the same protocol. The machines in the equipment population operated in a similar environment, under a similar duty cycle and load conditions to include use of similar fluids

and capacities. Where machinery is maintained as such, it remains part of the same population, regardless of age.

6.1.4 An optimum sample interval has been established accounting for the likely or expected failure modes and at least two samples will be available between failure mode initiation and its terminal phase.

6.1.5 The data set should represent historical measurements covering at least one overhaul interval or in the case of a large fleet, should cover all operational phases from new to overhaul.

6.1.6 Each established measurand is free from interference.

6.2 The following comments only apply to parametric data for which the data set fits a normal distribution:

6.2.1 The population satisfies a normal distribution in accordance with Practice **D6299** Anderson-Darling (A-D) statistic which is used to objectively test for normality as described in Subsection A1.4 of Practice **D6299**, or in accordance with an equivalent test for normality.

6.2.2 Most WHITE and GREEN level alarm data are expected to fall within two standard deviations of the mean or represent about 94 % of all samples taken.

6.2.3 Abnormal sample data are expected to fall outside two standard deviations of the mean and represent about 6 % of all samples taken. These data are expected to exceed a YELLOW level alarm and unacceptable performance or an indication of a degrading condition is expected.

6.3 When using cumulative distribution technique for parametric data, alarm limits may be set at points that do not coincide with standard deviations.

6.4 Careful consideration should be given to the grouping of a population. Improved accuracy to the alarm values and limits being generated can be obtained by dividing a larger group of less similar equipment/machinery into smaller more similar ones.

6.5 Alarm limits that are deemed to be practical must be tested at a minimum using the data set from which they were derived to demonstrate that the functional conclusions are verifiably correct.

6.6 Other statistical methods beyond those stated within this guide may also provide reliable and useful alarm limits. This guide is limited to those discussed in Section 7 as they can be readily applied without extensive statistical training. This guide does not intend to preclude the use of other statistical models.

6.7 Alarm limits may be or may have been developed by OEMs based upon experience, or in house data, or both. These recommendations may be based upon current information or they may have been generated by a company that no longer manufactures the equipment.

6.7.1 For the case of limits based upon current data, these limits can have great value for product support and maintenance. This guide should be considered when variations in usage and maintenance may occur. The user who wishes to depart from OEM suggested alarm limits should consider contact and discussions with the OEM when deviations from their defined limits are made.

6.7.2 For the case of limits based upon old data or from a company that no longer produces or supports the product, changes in lubricants or maintenance practices may have an effect on the OEMs limits provided. These limits may be used as a starting point for limits as discussed in 7.2.2. The techniques stated within this guide would be expected to aid the quality and accuracy of these limits.

7. Procedure

7.1 In-service lubricant sample analysis is commonly used for condition monitoring of lubricant characteristics, lubricating system contamination, and equipment wear. Samples are periodically and consistently collected from designated sample points on equipment and are analyzed either by an off-site laboratory, by an on-site laboratory, by on-site test kits or by in-line sensors.

7.1.1 Analyses typically involves multiple tests that produce several measurands (also called analysis parameters) which have been intentionally selected to report and measure characteristics covering the intended range of conditions to be monitored. The group of tests (for example, test profile) is intended to target selected characteristics associated with the asset or equipment type being monitored and produce a list of measurands called a measurand set (also called analysis parameter set). It is common to have three alarm limits between four alarm levels associated with each alarm-based measurand. Alarm limits may be upper or lower or upper and lower depending on the nature of each measurand. The combination of all the alarm limits for a complete measurand set is called an alarm limit set.

7.1.2 It is not necessary for every measurand to have alarm limits. Measurand and data values that are not alarm-based have other uses such as supporting, correlating, or validity checking.

7.1.3 Measurand based alarm limits serve as an intermediate contribution in a process for condition monitoring. Work orders and maintenance actions are based on a review of all data from a measurand set, on historical data and on other information for a measurement point.

7.1.4 This procedure outlines two techniques to statistically evaluate alarm limits applied to data from in-service lubricant analysis condition monitoring: a statistical process control technique and a cumulative distribution technique. Both of these techniques depend on statistical information from multiple data sets where each data set corresponds to a measurand. And the combination of multiple data sets covers all the alarm-based measurands within a measurand set.

7.2 *Equipment Population*—There are many types of equipment in a condition monitoring database. A particular type of equipment is selected for an equipment population that includes a large number of similar equipment items having the same lubricant and operating under similar conditions. A list of all measurands from a lubricant sample test profile selected for an equipment population results in a measurand set representing characteristic measurements selected to reveal likely modes and causes of degradation or failure for the lubricated machinery and for the lubricants.

TABLE 1 Generic Example

How to create a measurand set for an equipment population?	
First, choose test of modes and causes. Here are examples:	Then, a measurand set will list measurands specified by your preferred methods, guides, and practices:
Particle counting	D6786, D7647, D7416, D7596
Ferrous density	D7416, other
Water-in-oil	D4928, D6304, D6439, D7416, E2412
Lubricant chemistry	D664, D974, D2896, D7414, D7416, D7484
Elemental Fe, Pb, Si, Ba, and Na	D5185, D6595
Lubricant viscosity	D445, D7042, D7279, D7416, D7483
Wear debris analysis	D7670, D7416, D7684, D7690, D7685

7.2.1 For each measurand for which the user wishes to evaluate alarm limits, the user produces a data set covering the equipment population. If the data set follows a parametric statistical distribution, then the user may apply statistical process control and cumulative distribution techniques to statistically evaluate alarm limit values. If the data set is nonparametric or if it includes special cause variation, then the user may apply cumulative distribution technique to statistically evaluate and make practical adjustments to existing alarm limit values.

7.2.2 Statistical analysis suggested in this guide is most effective using large sets of measured data values (≥ 30) for each alarm-based measurand. Historical data is necessary for statistical analysis. Thus, this guide is typically used to evaluate and adjust alarm limits. If sufficient historical data is not available, alarm limits for similar or related equipment can be used as a starting point until limits can be generated for the specific equipment. Other get-started alarm limits may be based on sources such as original equipment manufacturers, lubricant suppliers, industry expert consultants. However, these alarm limits should be migrated toward statistically based alarm limits as data becomes available.

7.2.3 The user of this guide will need access to a historical database containing the following information:

7.2.3.1 Equipment information for lubricated machinery and other equipment,

7.2.3.2 Lubricant identity for the lubricant used in each lubricant compartment,

7.2.3.3 An equipment population listing a set of like equipment based on similarity of equipment information and lubricant identity,

7.2.3.4 Failure modes and causes for common problems within the equipment population,

7.2.3.5 A measurand set listing in-service sample test measurands which can identify modes and causes, and

7.2.3.6 Preferably not less than 30 historical measurand data values within the data set used with each measurand for statistical evaluation of alarm limits.

7.2.4 As mentioned earlier, the user studies detail equipment information to designate an equipment population made up of similar equipment, using same lubricant, and operating under similar load, operation, and environmental conditions. Within an equipment population it is possible to have the same type of equipment that is both critical equipment, such as important production assets that are not redundant or high value or highly sensitivity or otherwise essential, as well as noncritical equipment, such as balance of plant equipment and redundant

assets. Statistical analysis of data from an equipment population including both critical and noncritical equipment is likely to be applied more conservatively when statistical results are used for evaluating or adjusting alarm limits for critical equipment as compared with noncritical equipment.

7.2.5 This guide works best with a segregated, well-behaved population of identical equipment so that common cause variation in measurand data values will be small and failure modes will be readily observable in the data.

7.2.6 It is recognized that for a laboratory with hundreds or even thousands of equipment variations, it may be time consuming to create, use, and manage dozens or hundreds of different alarm limit sets. Therefore practical application of this guide may require compromise trade-offs when selecting specific equipment for inclusion in a statistical equipment population. The limitation in the quality of alarm limits generated in this fashion should be recognized.

7.2.7 It is common practice for users to designate equipment in categories such as pumps, motors, compressors, gearboxes, steam turbines, gas turbines, diesel engines, etc. Further dividing these down by make and model is desirable, particularly for fleets. Still further dividing groupings down by speed, duty cycle, and load will yield the best alarms.

7.2.8 If a user groups equipment from too many different equipment types or operational functions, then it becomes difficult to assure that resulting alarm limits are relevant and statistically accurate. If there are too few pieces of equipment in the population then variation of measured data within each population becomes too broad causing some problems not to get alarmed, while others are prematurely flagged.

7.3 *Modes and Causes*—For each equipment population, the user creates or selects an appropriate measurand set, which, includes a list of measurands covering many of the commonly experienced failure modes and root causes (“modes and causes”) of component and lubricant. To demonstrate this point, an exemplary discussion is provided in the following paragraphs about how to create a measurand set that covers a few commonly experienced modes and causes of undesirable wear conditions such as abrasive wear, premature fatigue wear, corrosive wear, and abnormal wear resulting from boundary lubrication. The discussion further suggests measurands to identify the condition of the equipment and lubricant used in the associated equipment population. **Table 1** is provided as a generic example of how to create a measurand set based on the discussion in the following paragraphs. Measurand sets and the logic behind them vary depending on equipment and lubricant

modes and causes of failure. There is more discussion on measurand data set distribution forms in 7.9 – 7.12 for typical measurand data sets referenced in Table 1. Additional examples for selecting tests and therefore measurands to make up a measurand set may be found in Practice D4378 and D6224 where various test options are specified for turbine oils and auxiliary power equipment.

7.3.1 *Abrasive Wear*³—Hard particle contamination of a lubrication system is a cause of abnormal abrasive wear in mechanical systems. Excessive abrasive wear is frequently caused by elevated dust contamination. Particle counting and measurement of the element, silicon, are two techniques to reveal a root cause for abrasive wear. Ferrous density measurement and wear debris analysis (atomic emission spectroscopy, ferrography) are two of many techniques to monitor wear such as abrasive wear. There are many other in-service lubricant sample tests one may perform to monitor cause and presence of abrasive wear.

7.3.2 *Fatigue Wear*³—Long-term dynamic loading of load bearing surfaces is a principal cause of fatigue wear in tribology. Excessive or premature fatigue wear is frequently caused by elevated dynamic loading. Other condition monitoring means such as vibration analysis are often used to ascertain information about root causes relating to elevated dynamic loading such as imbalance, resonance, or misalignment. Three of many different in-service lubricant sample measurements capable of detecting the onset and progression of fatigue wear include ferrous density, wear debris analysis, and elemental metals analysis.

7.3.3 *Corrosive Wear*³—Corrosive fluid contamination of lubrication systems is a principal cause of corrosive wear in tribology. Excessive corrosive wear is frequently caused by elevated water-in-oil or by contamination with another corrosive liquid or gas such as water based coolant or a corrosive process material. Three of many in-service lubricant sample measurements capable of detecting corrosive fluids contaminating a lubricating system are these: water-in-oil, elemental analysis for detecting a coolant additive such as sodium (Na) and for detecting corrosive wear such as iron (Fe) and lead (Pb), and relative permittivity or acid number or base number indicating the lubricant has either gained acidity or lost alkalinity. For this discussion we will include one or more measurands appropriate for measuring water-in-oil, acid number, base number, or elemental Na, Fe, and Pb.

7.3.4 *Wear Due to Boundary Lubrication Failure*³—Boundary lubrication wear is the result of transferring at least a portion of bearing load between moving surfaces though metal to metal contact when the fluid film is not fully supporting load. Anti-wear (AW) and extreme pressure (EP) additives are often used to combat effects of friction and wear under boundary lubrication conditions. AW and EP additives may be physically adsorbed or chemically reacted soft films (usually very thin) that help support contact loads. Nonetheless, under boundary lubrication some wear is inevitable. Excessive wear in boundary lubrication regimes often

results from inadequate lubrication conditions such as (A) lubricant supply is insufficient, (B) mechanical loading is too high, (C) machine speed is too slow, or (D) lubricant viscosity too low. Measurands from particle counting, microscopic wear debris analysis, elemental analysis, and viscosity are a few examples of tests capable of detecting this failure.

7.3.5 *Lubricant Degradation*³—Lubricants are susceptible to chemical degradation from prolonged elevated temperature and exposure to oxygen sources such as moisture or aeration. There are various in-service lubricant sample tests one may use to verify identity and state of degradation for a lubricant. Often these will include tests for viscosity changes (such as a kinematic viscosity testing) and tests for significant chemical changes in lubricant chemistry (such as Fourier Transform Infrared, relative permittivity, acid number, or base number). Measurands from selected tests are included in the measurand set.

7.3.6 *Lubricant Mixing*—Mixing or misapplication is another common problem that should be detected and corrected.

7.4 *Alarm Levels*—An alarm is a means of alerting the operator that a particular condition exists. An example of four distinct levels of alarm states is provided with this guide. They are WHITE, GREEN, YELLOW, and RED. Fewer or more distinct levels may be used. Additional nomenclature for these levels is provided in Section 3.

7.4.1 Alarm limits are the values representing greater-than or less-than thresholds between these levels of alarm.

7.5 *Statistical Process Control (Spc) Techniques for Evaluating Alarm Limits:*

7.5.1 SPC is used to evaluate alarm limits for a measurand data set population that fit a statistically normal distribution. Calculate the standard deviation for the data population. Fig. 1 graphically represents a parametric, normal distribution.

7.5.1.1 SPC “One-Sigma Limits”—68.27 % of data set values will fall within one standard deviation of the population mean. Sample data within less than or equal to one standard deviation of the center line (for example, approximately equal to statistical mean) may be comparable to a WHITE alarm level.

7.5.1.2 SPC “Two-Sigma Limits” or “Warning Limits”—94.45 % of samples will fall within two standard deviation of the population mean. Sample data greater than one standard deviation away from the center line and less than or equal to two standard deviations away may be comparable with a GREEN alarm level.

7.5.1.3 SPC “Three-Sigma Limits” or “Control Limits”—99.73 % of samples will fall within three standard deviation of the population mean. Abnormal to failure conditions are suggested by measurand data greater than a second and less than or equal to a third standard deviation away from the center line may be comparable with a RED alarm level.

7.5.1.4 SPC “Four-Sigma Variance”—99.99 % of samples will fall within four standard deviation of the population mean. Assignable or special cause variance is often suggested for data exceeding three standard deviations from the population mean.

7.5.1.5 Outlier values identified using accepted statistical techniques should be removed from the data set populations as outliers. Once removed, the statistics should be reevaluated.

³ Toms, Larry A., and Allison M. Toms, *Machinery Oil Analysis - Methods, Automation and Benefits*, 3rd edition, STLE, Park Ridge, IL, 2008.