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Standard Practice for Lubrication and Hydraulic Filter Debris Analysis (FDA) for Condition Monitoring of Machinery[1]

This standard is issued under the fixed designation D7898; 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.

INTRODUCTION

The purpose of this practice is to describe best practice methods for the analysis of filter debris from machinery lubrication or hydraulic systems primarily for the purpose of machinery condition monitoring. The purpose of Filter Debris Analysis (FDA) is to determine the health of oil-wetted machinery by analyzing the size, quantity, morphology, and composition of debris trapped by the system filter. FDA is emerging as an important condition monitoring technique as fine filtration becomes more common and the associated reduction of metallic particulates makes traditional elemental analysis of the lubricant less effective. System filters have an added advantage over traditional sample-based techniques in that they capture a high percentage of the total system debris (metallic, non-metallic, and organic particulate contamination) within the size range useful for machinery condition monitoring.

1. Scope

1.1 This practice is intended to cover the extraction, analysis, and information management pertaining to visible wear debris collected from oil system filters or debris retention screens. Further, it is intended that this practice be a practical reference for those involved in FDA.

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

1.3 *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.*

1.4 *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]

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

D7720 Guide for Statistically Evaluating Measurand Alarm Limits when Using Oil Analysis to Monitor Equipment and Oil for Fitness and Contamination

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

F316 Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test

G40 Terminology Relating to Wear and Erosion

D4175 Terminology Relating to Petroleum Products, Liquid Fuels, and Lubricants

2.2 *Other Standards:*

TTCP-AER-TP3-TR01-2010 Guide for Filter Debris Analysis[3]

[1] This practice is under the jurisdiction of ASTM Committee D02 on Petroleum Products, Liquid Fuels, and Lubricants and is the direct responsibility of Subcommittee D02.96.06 on Practices and Techniques for Prediction and Determination of Microscopic Wear and Wear-related Properties.

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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.

[3] Published by the Technical Co-operation Program (TTCP), July 2010.

3. Terminology

3.1 *Definitions:*

3.1.1 *abrasive wear, n*—wear due to hard particles or hard protuberances forced against and moving along a solid surface. **D4175**

3.1.1.1 *Discussion*—Also called cutting wear in some instances such as machining swarf.

3.1.1.2 *abrasive wear particles, n*—long wire-like particles in the form of loops or spirals that are generated due to hard, abrasive particles present between wearing surfaces of unequal hardness; sometimes called cutting wear particles or ribbons. **D7684**

3.1.1.3 *three body abrasive wear, n*—form of abrasive wear in which wear is produced by loose particles introduced or generated between the contacting surfaces. **D7684**

3.1.1.4 *two body abrasive wear, n*—form of abrasive wear in which the hard particles or protuberances that produce the wear of one body are fixed on the surface of the opposing body. **G40**

3.1.2 *adhesive wear, n*—wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or loss from either surface. **G40**

3.1.2.1 *Discussion*—Also called sliding wear or rubbing wear.

3.1.2.1 *rubbing wear particles, n*—particles generated as a result of sliding wear in a machine, sometimes called mild adhesive wear. Rubbing particles are free metal platelets with smooth surfaces, from approximately 0.5 to 15 µm in major dimension and with major dimension-to-thickness ratios from about ten to one for larger particles to about three to one for smaller particles. Any free metal particle <5 µm is classified as a rubbing wear particle regardless of shape factor unless it is a sphere. **D7684**

3.1.2.1 *Discussion*—Rubbing particles can also be attributed to the benign removal of asperities (polishing) of wear surfaces during run-in of machine.

3.1.2.2 *severe sliding wear particles, n*—in tribology, severe sliding wear particles are >15 µm and several times longer than they are wide. Some of these particles have surface striations as a result of sliding, and they frequently have straight edges. Their major dimension-to-thickness ratio is approximately ten to one. **D7684**

3.1.2.1 *Discussion*—Severe Sliding Particles can be generated as a result of inadequate lubrication, wrong lubricant, extreme loading, or no lubricant. Ferrous particles can often exhibit heat tinting coloration on their surface as a result of the high frictional temperatures experienced during this process.

3.1.3 *asperity, n*—a protuberance in the small-scale topographical irregularities of a solid surface. **G40**

3.1.4 *contaminant particles, n*—particles introduced from an extraneous source into the lubricant of a machine or engine. **D7690**

3.1.5 *debris, n*—in tribology, particles that have become detached in a wear or erosion process. **G40**

3.1.6 *debris, n*—in tribology, solid or semi-solid particulate matter introduced to lubricant through contamination or detached from a surface due to wear, corrosion, or erosion process. **D7684**

3.1.7 *debris, n*—in internal combustion engines, solid contaminant materials unintentionally introduced into the engine or resulting from wear. **D4175**

3.1.8 *filter debris analysis (FDA), n*—in tribology, a process for extracting and inspecting debris accumulated on the filter media taken from an in-line circulating lubricating system. **D7684**

3.1.9 *non-ferrous metal particles, n*—free metal particle composed of any metal except iron. All common nonferrous metals behave nonmagnetically except nickel. **D7690**

3.1.10 *nonmetallic particles, n*—particles comprised of compounds, organic material, glasses, etc. that have bound electrons in their atomic structure. **D7690**

3.1.10.1 *nonmetallic amorphous particles, n*—particles without long range atomic order that are transparent and that do not appear bright in polarized light. **D7690**

3.1.10.2 *nonmetallic crystalline particles, n*—particles with long range atomic structure that appear bright in polarized light. These may be single crystals but are most likely polycrystalline or polycrystalline agglomerates. **D7690**

3.1.11 *rolling contact fatigue, n*—damage process in a triboelement subjected to repeated rolling contact loads, involving the initiation and propagation of fatigue cracks in or under the contact surface, eventually culminating in surface pits or spalls. **G40**

3.1.12 *scoring, n*—in tribology, a consequence of severe sliding wear characterized by formation of extensive grooves and scratches in the direction of sliding; also called striation. **D7684**

3.1.13 *spalling, n*—in tribology, the separation of macroscopic particles from a surface in the form of flakes or chips, usually associated with rolling element bearings and gear teeth, but also resulting from impact events. **G40**

3.1.14 *wear particles, n*—particles generated from a wearing surface of a machine. **D7684**

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *debris, n*—particulate recovered from a machine containing both wear-related, benign (for example, residual overhaul swarf), or organic material, or combinations thereof, foreign to the system.

3.2.2 *Feret's diameter, n*—the largest distance between two parallel lines that just touches the edge of an irregularly shaped particle. Also known as calliper diameter.

3.2.3 *ferrous debris, n*—metallic debris consisting mainly of iron (Fe) and exhibiting ferro-magnetic behavior (that is, the material is attracted or repelled when exposed to a magnetic field). Recommended abbreviation: Fe.

3.2.4 *filter bypass system, n*—a system by which circulating fluid can bypass the filter element if the differential pressure across the filter becomes excessive due to blockage by contamination. Under bypass conditions, fluid can continue to circulate but will be unfiltered.

3.2.5 *filter debris, n*—any matter captured in a system filter element.

3.2.6 *filter patch, n*—a piece of filter material of known permeability (mesh opening dimension) used to capture debris sized greater than the rated mesh opening; usually specified in µm. Also known as membrane patch.

3.2.7 *filter patch mesh size, n*—the diameter of the largest sphere that can pass through the filter patch mesh opening.

3.2.8 *fine filtration, n*—filtration applied to a lubrication or hydraulic system that meets or exceeds a Beta ratio of 200 for 5 µm (c) particles (that is, $\beta_{5(c)} \geq 200$).

3.2.9 *graticule, n*—fine lines of known spacing used to determine the scaling of microscopic images.

3.2.10 *metal map, n*—a list of components within a machine by part number or function together with the component's alloy specification and composition. Also known as materials atlas or component material specification list.

3.2.11 *parent system, n*—the mechanical system from which the debris sample originated from, for example, helicopter main rotor gearbox.

3.2.12 *particle areas, n*—this measurement is used by some aircraft manufacturers to define the criticality of wear debris. It is not recommended since it is almost impossible to obtain an accurate measurement of an individual particle in the field without using appropriate particle image processing software.

3.2.13 *particle aspect ratio, n*—the length of a predominantly two-dimensional particle divided by its width.

3.2.14 *rolling contact fatigue particles, n*—these particles are generated in a load/unload (cyclic) environment and is a typical failure mode for rolling element bearings and gears. Particles are generated when subsurface cracks, generated by the significant sub-surface shear stress associated with Hertzian contact stresses, propagate to a point where a spall is liberated from the load surface. These particles can be tens of microns up to millimetres in length. Particles may show evidence of the machined load-bearing surface on one face and a rough crystalline surface (where the crack propagated) on the reverse. Particles may be rolled and reworked by subsequent rolling elements or gear teeth and may then appear as a flattened flake with characteristic radial cracking from the edges and a fissured or crazed edge. Particles are hard and brittle, not deformable without cracking when load is applied.

3.2.15 *scale bar, n*—a reference measurement embedded into or applied on an image to enable scaling of other objects present in that image. The units of measurement must be clearly presented with the scale bar.

3.2.16 *striations, n*—fine parallel lines or scores on a particle surface.

3.2.17 *slurry, n*—mixture of debris suspended in solvent.

3.2.18 *wear debris analysis, n*—the analysis of metallic debris with particular emphasis on size, count, morphology, and composition. May also provide some indication of the criticality.

3.2.19 *wear particle atlas, n*—a compilation of high resolution images showing the key features of the different types of pure wear debris (fatigue, adhesive, and abrasive).

4. Summary of Practice

4.1 Lubrication and hydraulic system filters are a rich source of information about system health that are seldom exploited for machinery condition monitoring purposes. This practice seeks to define some procedures that ensure consistent extraction and analysis of filter debris in order to assess system health.

5. Significance of Use

5.1 The objective of FDA is to diagnose the operational condition of oil-wetted machinery systems in order to identify abnormal wear or incipient component failures. Oil system filters (typically lubrication system or hydraulic systems) capture the vast majority of metallic and non-metallic debris generated or contained within a system. The exploitation of this potential source of information for machinery condition monitoring purposes has been difficult in the past due to the absence of a clear automated or manual method for extracting, analyzing, reporting, and archiving the debris. This practice is provided to enable a consistent approach to the analysis of in-service debris captured in filters and is intended primarily for lubrication or hydraulic systems.

5.2 Caution shall be exercised when drawing conclusions based on particle quantity, composition, and morphology. Any maintenance or operational actions shall be carefully considered and take into consideration any extant limits provided by the manufacturer as well as any historical information known about the subject system.

6. Filter Elements

6.1 Filter elements may be broadly classified as either reusable or disposable. Prior to processing a filter element, it should be understood whether the element is disposable or reusable so that appropriate processing techniques can be applied.

6.2 This is to ensure disposable elements are not inadvertently reused following extraction of debris.

6.3 Reusable filter elements are typically made from sintered metal or woven metal fiber (mesh), but can also employ other media types.

6.3.1 If a reusable filter is to be reinstalled into a machine, then the filter element should be treated as a serviceable part, and as such the following observed:

6.3.1.1 Any process, solvent, etc. used to extract wear debris must be in accordance with the approved maintenance manual. This will typically include a predefined cleaning and drying procedure that must be conducted prior to reinstalling the element. Failure to follow approved procedures could result in degraded filter performance or contamination of the oil system with residual cleaning solvent, or both. Some filters may require a bubble point test (for example, Test Methods F316) to confirm the integrity prior to reinstallation.

6.3.1.2 If the approved maintenance manual does not specify a suitable method for cleaning the reusable filter that sufficiently extracts debris for analysis, then the filter element manufacturer should be consulted to determine an appropriate

method. Ultrasonic extraction in particular can cause visually undetectable damage to some reusable filter media.

6.3.1.3 The number of times a filter can be cleaned and reused should also be determined. Some reusable filter elements will only tolerate a finite number of cleaning processes before becoming degraded beyond acceptable performance limits. Where a maximum permissible number of cleans is determined, this needs to be tracked (for example, engraving an inspection marking on the filter element each time it undergoes cleaning/debris removal).

6.4 Disposable filters are intended for single use and should not be reused once removed from the machine for FDA.

6.4.1 The specific filter media in these types of filter varies but are typically made of one of the following materials:

(1) Cellulose fiber

(2) Fiberglass

(3) Ceramic

6.4.2 As disposable filters are not reinstalled in machinery, any method that best extracts debris may be used.

6.4.3 Where screw-on cartridges are used, if manually cleaning, the cartridge outer casing may need to be cut open to reveal the filter element.

6.4.3.1 This is best achieved using a dedicated filter cutter (Fig. 1) that uses a continuous cutting action similar to a domestic can opener; sawing should be avoided as it generates substantial swarf that can become intermixed with the true wear debris. Note, there is still the possibility of swarf contamination from the casing material.

6.5 The procedure by which a filter element is removed from a system and prepared for wear debris sampling should be defined and consistent.

6.5.1 Often a significant amount of oil containing debris can drain from the filter element when removed or may remain in the filter bowl/housing assembly.

6.5.2 The quantity of residual oil will be different for each specific system filter assembly design; therefore, it is recommended a specified procedure be developed for each type as appropriate.

6.5.3 The following filter removal process is recommended:

FIG. 1 Example of a Filter Element Cutter

6.5.3.1 *Filter Element*—Remove filter element and place it vertically in a clean tray, allow residual oil to drain off for approximately 1 min. The drained filter element may then be prepared for wear debris extraction. If debris extraction is to be done off site (for example, in a laboratory) package filter (see Note 1), indelibly label, and dispatch to the analyzing laboratory with documentation relevant to the parent machine (machine serial number, aircraft tail number, date the filter was removed, hours filter installed, location, and reason for removal). If debris extraction is to be done on site, carry out extraction using manual or automated method as appropriate.

NOTE 1—When sending filter elements or oil samples, they must be packaged in accordance with local rules to ensure oil does not leak out and to also prevent ingress of foreign debris. Typically this involves placing the item in two containers and placing absorbent material in the box around the bagged items.

6.5.3.2 *Residual Oil*—Inspect the residual oil drained from the filter element itself and residual oil in the filter bowl assembly (if applicable). If debris is visible, then collect the residual oil/debris in a clean bottle, indelibly label the bottle, and dispatch with the filter element to the analyzing laboratory. If no debris is present, then dispose of residual oil appropriately. Debris greater than 100 µm can appear as scintillating particles in the oil when backlit illumination is applied (for example, flashlight).

7. Extraction of Filter Debris

7.1 The exact process to best extract filter debris is somewhat dependant on the filter type, equipment and personnel available. If filter debris is to be robustly trended, the established method for debris extraction should be applied consistently and subject to process controls. Semi and fully automated filter debris extraction equipment can offer significant benefits in this regard.

7.2 The manual extraction method involves simple equipment that can effectively extract debris from a filter element and is particularly useful where machinery is employed in remote localities.

7.2.1 The manual extraction process is shown in Annex A1.

7.2.2 The following items (or their equivalent) will be required to manually extract debris from a filter element:

7.2.2.1 A sealable robust (impact resistant) polypropylene cylindrical bottle;

7.2.2.2 Rubber stoppers to plug the filter element clean oil exit port(s);

7.2.2.3 A suitable solvent. This will vary depending on the oil used.

7.2.2.4 A flusher bottle or tweezers to enable persistent debris to be removed from the element.

7.2.3 When this method and its associated equipment are used for filter elements from different machines, a strict cleaning regime is essential to prevent possible cross-contamination and subsequent false attribution of FDA results.

7.2.3.1 To achieve this, all equipment should be cleaned prior to and following each filter debris extraction (that is, a double clean). In particular, the sealable bottle should be cleaned using a small quantity of clean solvent followed by a thorough wipe out using lint-free disposable cloth.

7.2.3.2 Appropriate personal protective equipment must also be used when handling solvents.

7.3 Ultrasonic agitation is an effective method for extracting debris from a filter element. This method requires the following equipment:

(1) Ultrasonic bath,

(2) Clean solvent, and

(3) A container to house the element and contain the subsequent slurry.

7.3.1 The following provides the recommended minimum processing time for ultrasonic bath extraction:

7.3.1.1 Five minutes where entire element is submerged in solvent and exposed to ultrasonic waves, followed by a further five minutes with the element inverted (vertical orientation).

7.3.1.2 Five minutes per side where only half of the element can be submerged in solvent and exposed to ultrasonic waves (horizontal orientation).

7.3.2 Some reusable filter elements cannot be cleaned using ultrasonic baths as damage to the element filter media may result.

7.3.2.1 Instead of ultrasonic extraction, an alternative method known as sub-sonic (or electro-sonic) extraction may be employed.

7.4 Removable diagnostic layers are available that can provide an effective means of removing significant debris from a filter element.

7.4.1 The removable outer layer is sacrificial and provides a rapid method of extraction.

7.5 Typical filter element designs use a folded pleat element design. Due to the flow path through the element, this results in debris collecting in the valleys of the pleats. Some filter media types can trap debris in these valleys, which the above methods cannot always remove. This is particularly the case for elements that do not have metallic wire gauze over the filtration media.

7.5.1 In this case, debris may be extracted by manually forcing apart adjacent pleats and using tweezers, etc. to remove large debris.

7.5.2 The filter media can also be removed by circumferentially cutting through the filter media top and bottom with a sharp instrument, removing, and flattening out the filter media. Annex A2 shows this process.

7.5.3 Once the media is removed, debris can be extracted by immersion in solvent and application of ultrasonic agitation.

7.5.4 In general, sectioning of filter elements is time consuming and should only be done if necessary or an in-depth analysis for a failure investigation is required.

7.5.5 Care should be taken to ensure debris generated by the cutting of the filter element is not mistakenly analyzed as wear debris.

7.5.6 The filter manufacturer should be consulted prior to cutting any filter media to identify any hazards associated with the filter media.

8. Preparation of Extracted Debris

8.1 Once the debris has been extracted and contained in a slurry, it must be captured to enable analysis to take place.

8.2 A filter patch is a piece of filter material of known porosity that will capture particulate of greater size than the rated porosity. Filter patches come in a variety of sizes; however, typically the filter patches are either 47 mm diameter or 25 mm diameter. Forty seven millimetre diameter patches are recommended for FDA.

8.2.1 Nylon filter patches in the 20 µm to 100 µm range have been found to be effective at capturing significant debris, while allowing finer particles, particularly oil degradation products, to pass through and prevent filter patch clogging.

8.2.2 The filter patch porosity may need to be a compromise of significant particle isolation and prevention of clogging; this can vary from system to system and should be determined from fleet experience for the actual system to be monitored.

8.2.3 In general, the following filter patch porosities are recommended to ensure significant debris is retained:

(a) 60 µm nylon filter patch is for lubricant filter analysis, and

(b) 20 µm nylon filter patch for hydraulic filter analysis.

Sequential filtering of the slurry in decreasing porosity (for example, 20 µm followed by 5 µm) can also be used to ensure fine debris is captured. This is typically only required in hydraulic systems where fine component tolerances exist.

8.2.4 Where high particulate concentration is encountered, a vacuum pump (hand or power) may be required to draw the slurry through the filter patch.

8.2.5 Filter patches finer than 20 µm are generally not recommended for FDA for the following reasons:

8.2.5.1 The severity of component wear is approximately proportional to particle size.

8.2.5.2 Experience has shown that generally particles less than approximately 100 µm captured in the filter are of limited practical use when diagnosing incipient wear-related failures.

8.2.5.3 However, for some systems, it may be appropriate to analyze smaller particles in order to detect failure modes that primarily produce “fines;” this is contingent on having equipment available to analyze such small particles as manual separation of individual particles is impractical.

8.2.5.4 Normal non-metallic filter debris (oil degradation products, sand, grit, etc.) have a propensity to rapidly clog these fine filter patches and obscure relevant wear particles by overlaying.

8.2.5.5 Where fine filter patches are made of cellulose, they can be extremely brittle and removing debris for further analysis extremely difficult.

8.3 Some equipment can extract debris automatically and then quantify the size of ferrous and non-ferrous debris for trending.

8.3.1 The output data from this type of instrument is via an inductive wear debris sensor (see Practice D7685).

8.3.2 The following particle size bins are recommended:

8.3.2.1 *Ferrous:*

(1) 100 µm to 250 µm

(2) 250 µm to 500 µm

(3) 500 µm to 1000 µm

(4) 1000+ µm

8.3.2.2 *Non-ferrous:*

(1) 500 µm to 1000 µm

(2) 1000+ µm

8.3.3 After passing through the inductive sensor, the debris is deposited on a filter patch to allow further elemental analysis if required.

8.3.4 Some equipment also incorporates elemental analysis capability.

8.4 Since the vast majority of load bearing elements of machinery are made from various alloy steels, the extraction and quantification of ferrous debris is a very useful step, particularly if equipment to quantify ferrous debris (inductive sensor) is not available.

8.4.1 Either a wet or dry method can be used for extracting ferrous debris from the extracted slurry. Both use a magnet to attract the ferrous debris and then deposit it on a separate receptacle for further analysis.

8.4.2 The dry method involves passing a magnetic tool over the parent filter patch in order to attract ferrous debris out of the bulk debris.

8.4.2.1 One of the simplest tools consists of a permanent magnet inner stem that fits into an outer non-magnetic sheath (Fig. 2).

8.4.2.2 The sheath tip is typically made of non-magnetic polymer. Inserting the stem into the sheath makes the sheath tip appear magnetic and enables debris to be attracted. Retracting the stem turns the tool off and allows the extracted ferrous debris to be deposited in a separate receptacle.

8.4.2.3 Alternatively a hand-held electro-magnet can be used.

8.4.2.4 Tools used for this technique should have a magnetic field strength of approximately 400 Gauss or greater.

8.4.2.5 Whilst the exact height that the tool is passed over the filter patch is not critical, it is recommended that the tool be within 3 mm to 7 mm from the filter patch surface.

8.4.2.6 Care should be taken to avoid contacting the tool with the surface of the filter patch as this can cause non-magnetic particles to be inadvertently collected via static or adhesion.

8.4.2.7 For this method to work effectively, the filter debris should have no residual oil and must be completely dry. If residual oil is suspected, then the filter patch may be rewashed using an appropriate solvent and dried.

8.4.2.8 To dry a filter patch, either place it in an oven at low temperature (40 °C to 60 °C) or allow to air dry. Alternatively, place the filter patch under a high wattage lamp (250 W minimum) until dry.

8.5 The wet method involves externally offering a magnet (with a magnetic strength of no less than 400 Gauss) to the slurry external to the container (usually a glass beaker) and then pour the remaining solvent slurry out while holding the magnet in place; the ferrous debris will remain in the beaker and can then be extracted onto a dedicated filter patch.

8.5.1 Alternatively, the magnetic tool in its sheath can be passed through the slurry until all ferrous debris is attracted to it.

8.5.2 The magnetic tool is then removed from the slurry, rinsed with solvent, and the magnet withdrawn allowing the ferrous debris to be deposited in a suitable receptacle.

8.6 Due to the size range of significant particles assessed in FDA (100 µm to 1000+ µm range), static can influence the analysis.

8.6.1 In particular, static can cause non-ferrous particles to inadvertently adhere to the sleeved magnetic tool during extraction of the ferromagnetic debris.

8.6.2 Without access to elemental analysis, non-ferrous particles could be erroneously counted as ferrous. To avoid

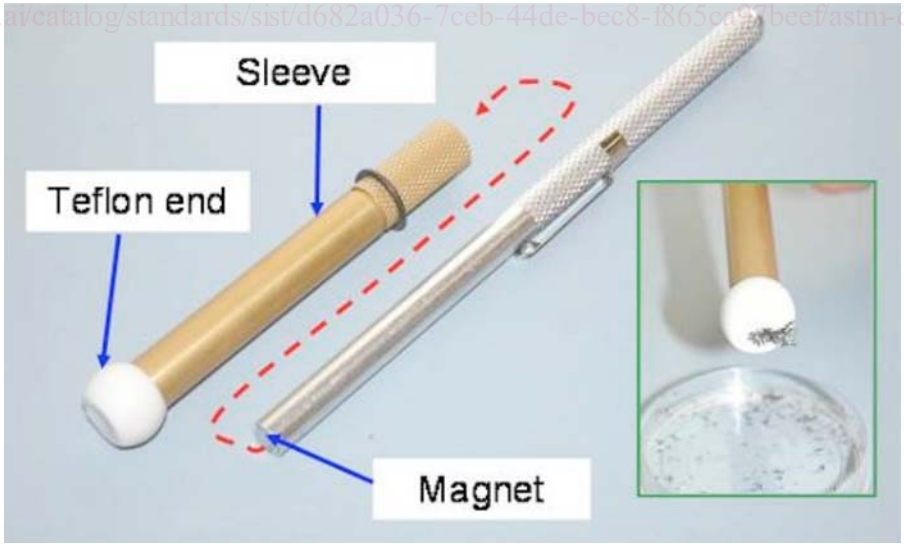

FIG. 2 Example of Sheathed Magnetic Tool

this, it is recommended that isopropyl alcohol swabs be used to clean the sleeved magnetic tool (or electromagnet) and are then allowed to dry thoroughly before use.

8.6.3 Excessive rubbing of the tool tip should be avoided if static is to be avoided.

9. Analysis of Filter Debris

9.1 The analysis of debris from a filter can be very time consuming if using manual techniques; however, the following guidelines are recommended to efficiently gain meaningful results.

9.2 Some equipment manufacturers may provide guidance on the quantity of debris allowable, and this should be followed.

9.3 FDA can include the assessment of quantity, size, color, morphology, elemental makeup, and alloy identification of significant debris extracted from the filter element.

9.4 The method of analysis will largely depend on the equipment available.

9.5 Particles are typically quantified using the following methods:

(1) Particle count (for example, visual or inductive debris sensor since conventional particle counters do not typically count particles greater than 100 µm),

(2) Non-dimensional number representing the magnetic flux change caused by a sample,

(3) Weight, or

(4) Inferred mass by inductive wear debris sensor.

9.5.1 A count of the particles in each of the desired size bins is usually accomplished manually or using particle counting software. Where extremely large quantities of debris are present, a minimum of 30 particles randomly selected from the sample is sufficient to form an inference of the bulk quantity.

9.5.2 A measure of the weight of the debris present requires sensitive scales to accomplish with any meaning.

9.5.3 One method for rapidly quantifying the debris from filter elements is to use a bench-top inductive or magnetic interference instrument. This method is particularly useful for rapid screening of filter elements or where there is no laboratory support.

9.5.3.1 After extracting the debris from the filter element, the sample is passed through the sensor where the size of the debris is inferred from the magnetic flux cutting capability of the sample.

9.5.3.2 The mass is then calculated by the instrument based on scaling from a known response to a spherical test particle of known size and made of a particular steel alloy.

9.5.3.3 These assumptions are a source of inherent overestimation of the mass when compared to the physically measured mass because wear particles are almost never spherical. Despite this, very useful information can be obtained if valid limits are set based on samples analyzed by that type of instrument.

9.5.3.4 Other instruments rely on the debris being suspended in oil; in order to use this type of instrument for FDA, it is possible to extract the debris from the filter element and then put the debris in an oil solution prior to analyzing. It is recommended that when using this type of instrument, a consistent volume of oil and sample/instrument interface area (that is, sample bottle diameter) are used.

9.5.3.5 Where an inductive instrument displays the output in terms of a physical unit (for example, mg or ppm), the results should be annotated in reports as inferred (for example, mg (*inferred*), or mg* with a footnote to that effect). This clearly discriminates between physically measured mass and inductively inferred mass.

9.5.3.6 Some instruments present the results in terms of non-dimensional numbers to avoid any confusion with physical units; however, these units tend to be less intuitive.

9.6 When quantifying particles, quantity descriptors can be used. The following descriptors are indicative only and will vary by machine size applications:

(1) Extreme: more than 100 particles present in sample;

(2) Large: 26 to 100 particles;

(3) Few: 6 to 25 particles; and

(4) Small: 1 to 5 particles.

9.6.1 Alternatively, the following quantity descriptors can be used: Extreme: greater than 50 % of all metallic particles; Large: between 10 % and 50 % of all metallic particles; Few: between 5 % and 10 % of all metallic particles; and Small: up to 5 % of all metallic particles.

9.6.2 The specific thresholds listed here can be adjusted for individual machinery.

9.6.3 It does not usually add value to an analysis to report oil degradation products (that is, soot granules), dirt, or sand unless these substances are present in extreme quantities.

9.6.4 Whilst the total number of particles is usually key to assessing the machinery health, two other important aspects for the analysis are:

(1) The rate of particle generation. This can only be determined if the number of installed filter operating hours are accurately known.

(2) A cumulative particle count. This approach could be considered over a suitable inspection period and captures information where ad hoc filter examinations can be called for within a set inspection period. For example, if a machine has a routine filter inspection every 200 h, then the results from any unplanned filter inspections that occur within the 200 h period should be added together and assessed collectively at the end of the usual period.

9.6.5 All sizes are measured by Feret's diameter for convenience.

9.6.5.1 The Feret diameter of particles can be measured in the field using a portable digital microscope or manually using precision vernier callipers.

9.6.6 Particle size distributions can be obtained by:

(1) Manual sizing (use of the filter patch mesh as an optical reference can be useful).

(2) Commercially available digital image analysis software (provided sufficient particle separation is achievable),

(3) Mechanical sieving, or

(4) Inferred size using an inductive sensor.

9.7 Morphology in the FDA context means an assessment of the particle characteristics or form as described in Guide

D7684. Additionally, Appendix X3 provides images of the key features relevant to wear particle identification.

9.7.1 Particle morphology assessment software or a recognized wear particle atlas may also aid morphological assessment.

9.8 An essential part of filter debris analysis is determining the elemental composition of the debris. This information combined with a metal map for the specific machine enables an accurate assessment to take place regarding criticality of the debris.

9.8.1 The two typical methods for obtaining elemental composition of debris are the Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) and X-ray Fluorescence (XRF).

9.8.2 Unless an automated piece of equipment is available, elemental analysis of every individual particle on a patch is generally not practical. Therefore, it is critical that debris of significance be identified and extracted from the population on the entire patch. This requires a small representative sample of each type of significant debris to be isolated for elemental analysis.

9.8.3 SEM EDS is an effective method for identifying the elemental composition of particles and in particular, the composition of individual particles of interest. It can, however, be time consuming to determine the composition of a large quantity of particles. In this case it is possible to use an area scan or analyze a randomly-selected representative sample of particles to infer the global composition.

9.8.4 X-ray Fluorescence (XRF) is a similar technique to SEM EDS and produces a similar elemental spectrum output. Instruments may provide a composite spectrum of the sample patch or individual particles may be analyzed. This depends on whether broad beam or narrow beam XRF is utilized and on the algorithms utilized for analysis (for example, fundamental parameters or spectral matching).

9.8.4.1 Typically XRF instruments are used to screen samples for the presence of tell-tale alloying elements or analyzing samples of single particles that have been extracted from the bulk sample. Statistical analysis of composite spectra results can be used to correlate various elemental profiles to be known failure modes.

9.8.5 Spectrometric Oil Analysis (SOA) has occasionally been used for filter debris analysis. Due to the inherent particle size limitation of this technique (that is, cannot resolve particles greater than approximately 8 µm), a process of acid digestion can be conducted first.

9.8.5.1 It is reported that metallic particles are placed in nitric acid (HNO_3), hydrochloric acid (HCL) and sulfuric acid (H_2SO_4) and then heated in a microwave oven to hasten digestion.[4] The resulting solution is then analyzed.

9.8.5.2 This method is not typically recommended since all size and morphological information is destroyed during the digestion process.

9.8.6 SEM EDS and XRF analysis reports can include a spectrum obtained from each sample and any related information for each of the typical alloying elements associated with ferrous debris. The minimum recommended reportable elements for ferrous debris are:

(1) Titanium (Ti)
(2) Vanadium (V)
(3) Chromium (Cr)
(4) Manganese (Mn)
(5) Iron (Fe)
(6) Nickel (Ni)
(7) Molybdenum (Mo)

9.8.7 If individual particles are analyzed, an exact alloy match can be determined by SEM EDS or narrow beam XRF analysis using spectral matching.

9.8.8 A significant amount of additional information can also be gained by identifying non-ferrous alloys. For example, many aeronautical rolling element bearings use silver plating as a sacrificial rub surface on bearing cages. Identification of silver plating flakes can indicate bearing distress has occurred, which can be a precursor to bearing failure.

9.8.8.1 Some machinery uses journal bearings typically with a bronze or Babbitt surface finish. Degradation of this type of bearing may generate bronze or Babbitt debris, or both, prior to failure.

9.8.8.2 Bronze particles will be indicated by copper based particles with typical alloying elements of lead and tin. Babbitt metal will typically be indicated by particles of varying compositions of lead, tin, and antimony.

9.8.9 The recommended minimum reportable elements for non-ferrous debris are:

(1) Silver (Ag)
(2) Copper (Cu)
(3) Lead (Pb)
(4) Tin (Sn)
(5) Zinc (Zn)
(6) Aluminum (Al)
(7) Magnesium (Mg)
(8) Antimony (Sb)

9.8.9.1 The above recommended reportable elements cover the typical alloys found in machinery; however, the metal map (if available) for the specific machine should take precedence when trying to identify elements of interest.

9.9 Microscopic examination is an important part of filter debris analysis.

9.9.1 Whether optical or digital microscopes are used, there are some fundamental requirements that must be met such as calibration of the image and annotation where light filtering has been used (for example, polarization or red/green filters).

9.9.2 Regardless of the type of microscope, it is recommended that a calibration image be taken to confirm the magnification level being used. This is usually achieved by imaging an object of known dimensions (usually a graticule or finely graduated precision ruler).

9.9.2.1 Once the image has been taken, a measurement is made (longest possible to minimizer error) and compared to the known measurement.

9.9.2.2 An error of less than 10 % is considered acceptable.

9.9.2.3 Once a calibration has been completed, a permanent scale bar of suitable length must be embedded into the image.

[4] Roylance, B. J. and Hunt, T. M., *Wear Debris Analysis*, Coxmoor, 1999, table 4.1.

9.9.2.4 Typical lengths used for scale bars associated with images of wear debris are 250 µm, 500 µm, 1000 µm; however, the length used is not critical provided it can be used to determine the size of other particles or objects in the image.

9.9.2.5 Where a filter patch is used, a measurement of the internal grid spacing can be used as a check prior to measuring particles.

9.10 Magnification of ×10 is usually available for in-field assessments; however, this will not usually provide sufficient detail for an accurate assessment to be made.

9.10.1 Modern portable digital microscopes that operate in conjunction with a computer can provide magnifications up to (and exceeding) ×200. In a laboratory, a magnification of at least ×40 is required to identify the requisite detail.

9.10.2 Microscopes typically capture reflected or transmitted light and in some cases both images might be required. For example, transmitted light might best reveal edge detailing, whilst reflected light is suitable for surface feature identification.

9.10.2.1 In order to capture useful information using transmitted light, the debris should be transferred to a glass slide or equivalent transparent substrate.

9.10.2.2 Should glare obscure the particle details, then polarized light can be used.

9.10.2.3 Other techniques have been used in the past such as green and red light filters.

9.10.3 Where non-traditional lighting techniques are used, an annotation on the image file name or in the caption should be made to that effect.

9.11 The rate of wear particle generation can provide a satisfactory indicator of incipient failure of components.

9.11.1 The rate can be based on the change in quantity of debris (count, mass, non-dimensional number) over a known interval.

9.11.1.1 The recommended interval for calculation of wear particle generation is operating hours of the specific machine. Calendar time may be used as an alternative depending on the machinery context.

9.11.2 The fundamental equation is as follows:

$$Wear\ Rate = \frac{Change\ in\ quantity}{Selected\ Interval} \quad (1)$$

10. Reporting

10.1 One essential part of FDA is the management of the associated data and traceability of the physical samples during and after an analysis has taken place. This is particularly important where FDA is undertaken as part of an investigation into an incident or accident. It is also important where opportunistic FDA is done by other agencies such as universities where rigorous procedures may not be in place.

10.1.1 It is essential that there be continuity of the evidence trail from the time the filter element is removed from the machine through to the report being released and subsequent archiving of the physical and electronic evidence.

10.1.2 At any stage of the process, either data or the physical debris must be able to be correctly related back to the parent system.

10.2 The purpose of this section is to provide guidance on how to ensure these requirements are met.

10.2.1 All samples must be traceable in terms of:

(1) The specific machine the filter came from,

(2) The system the filter came from (for example, gearbox serial number, etc.)

(3) The date the filter was removed from the machine,

(4) The time the filter had been in service (that is, installed time) to determine rate of wear, and

(5) The reason for filter removal.

10.2.2 All particles removed from the filter element for further processing must be traceable back to the parent system.

10.2.3 All analytical data (including images) and reports associated with the analysis must be traceable back to the actual sample and hence parent system.

10.3 To meet the traceability requirements, the following procedures are recommended:

(1) All sample holders and sample containers must be indelibly marked, labelled, or coded at all stages of processing.

(2) Each sample should be processed and stored in separate enclosures (that is, filter debris from a given parent system should have its own receptacle or sample holder).

(3) All reports and electronic data (such as images) should use a consistent file naming convention that enables traceability back to the parent system and either the processing date or filter removal date.

(4) Where adhesive stubs are used for SEM EDS analysis, particles cannot easily be retrieved from the adhesive stub following analysis. In this case, the particle and adhesive patch can be removed from the stub and placed in a labelled container. Alternatively, the entire stub can be archived so that inadvertent damage to particles does not occur.

10.4 It is recommended that upon completion of the FDA, all physical debris be placed in a suitable container and archived for a suitable period. The duration of archiving is dependant on local requirements; however, it is recommended that all physical debris from a filter be kept for a minimum of six months. Electronic reports and data pertaining to the report should also be archived in accordance with local requirements.

10.5 Ideally, the report summary should be limited to one page; however, additional information such as SEM EDS reports or images of significant debris can be added as appendixes as required. Appendix X1 contains a suggested format for the reporting of FDA results.

10.5.1 Prior to release, the report should be electronically locked to prevent alterations or tampering.

10.5.2 The FDA Triplex plot is included as a simplified alternative for reporting the results of FDA. The Triplex plot can be quickly and intuitively interpreted by personnel who are not skilled in the assessment of wear debris analysis.

10.5.2.1 The plot can be used where no explicit guidance is provided by the machinery manufacturer for the assessment of filter debris.

10.5.2.2 It is recommended that this type of plot be used as a screening tool to identify where further deeper-level analysis is required.

10.5.2.3 The plot is shown in Appendix X2 (Fig. X2.1) and consists of a series of concentric color zones (green, yellow, and red) representing three index values (1, 2, and 3) used to assess each segment.

10.5.2.4 Three segments represent a Size-Count index, Morphology Index, and a Composition Index.

10.5.2.5 The Size-Count index is a simplified metric used to summarize the size and quantity of debris found in the various categories and size ranges.

10.5.2.6 It can be used when a particle size distribution is produced either by manual counting or using suitable software.

10.5.2.7 Table 1 shows the matrix used to determine the Size-Count index.

10.5.2.8 The index is read off the matrix by simply intersecting the size row with the quantity column.

10.5.2.9 The numerically highest of the four indices (one for each recommended bin size) is then plotted on the FDA Triplex plot in the Size-Count segment.

10.5.2.10 Where inferred mass is used as a metric, the Size-Count index can be replaced by a Mass Index shown in Table 2.

10.5.2.11 The thresholds can be adjusted for specific machinery and operating context (consequence of failure).

10.5.2.12 The Morphology Index is a simplified metric used to identify the more significant wear modes and is shown in Table 3.

10.5.2.13 Each wear mode is allocated a numerical index that is plotted on the appropriate axis.

10.5.2.14 Whilst this is somewhat subjective, fatigue and adhesive wear are typically the primary wear modes of concern.

10.5.2.15 The allocation of indices can be modified based on known failure modes of a particular system.

10.5.2.16 The Composition Index is a simplified metric used to rank alloys by importance.

10.5.2.17 For typical machinery, alloys associated with bearings, gears, couplings, and shafts are rated as important.

10.5.2.18 Components associated with known failure modes that contribute to the system unreliability or unavailability should also be included.

10.5.2.19 Table 4 shows the Composition Index.

10.5.2.20 The plot functions as follows:

(1) The analysis results are translated into indices as described above.

TABLE 1 Size-Count Index

	Quantity			
Size	Small 1–5 particles	Few 6–25 particles	Large 26–100 particles	Extreme >100 particles
Very Large 1000+ µm	2	3	3	3
Large 500–1000 µm	2	2	3	3
Medium 250–500 µm	1	2	2	3
Small 100–250 µm	1	1	2	2

TABLE 2 Inferred Mass Index

Reported Mass	Mass Index
>100 mg (inferred)	3
50–100 mg (inferred)	2
<50 mg (inferred)	1

TABLE 3 Morphology Index

Morphology Descriptor	Morphology Index
Fatigue	3
Adhesive	3
Inconclusive	2
Abrasive	1

TABLE 4 Composition Index

Composition Descriptor	Composition Index
Unimportant Alloys (such as alloys known to be associated with overhaul debris or components where there is inherent redundancy)	1
Alloys of unknown importance	2
Known Important Alloys (such as bearing steels, gear steels, and shaft steels)	3

(2) A vector is drawn from the origin of the plot out to the center of the relevant segment at a radius corresponding to the allocated index.

(3) If any one vector enters the red zone (index value of 3) then further detailed investigation or maintenance is recommended (Fig. X2.2).

10.5.2.21 If two or more vectors enter the red zone, then maintenance action, a supplementary FDA, or deeper investigation should be undertaken at the earliest opportunity (Fig. X2.3 and Fig. X2.4).

11. Establishing Limits

11.1 Priority should be given to any limits published by the machinery manufacturer.

11.2 Where no published or endorsed limits exist for FDA, it may be necessary to establish limits.

11.2.1 It is important that feedback from machinery overhaul/teardown inspections be regularly reviewed to ensure FDA limits are appropriate (that is, not too low causing premature rejection, or too generous allowing damage progression to the point that might cause serious damage to machinery or personnel).

11.3 Guide D7720 provides guidance on setting statistical limits.

12. Correlation

12.1 One of the most important aspects of accurate diagnosis or prognosis is correlation of filter debris analysis with other condition monitoring techniques where possible.

12.2 Correlation with techniques such as vibration analysis can provide added confidence to a maintenance action decision.

12.3 Whilst it is acknowledged that this is not always possible, it should remain an aspirational aim of any FDA program.

13. Acknowledgement

13.1 A substantial component of this practice has been derived from the Guide for Filter Debris Analysis, TTCP-AER-TP3-TR01-2010, published by The Technical Co-operation Program (TTCP).

14. Keywords

14.1 filter debris analysis; machinery condition monitoring; wear debris

ANNEXES

(Mandatory Information)

A1. PROCEDURE FOR MANUAL FILTER DEBRIS EXTRACTION

NOTE A1.1—This procedure is suitable for filter elements up to approximately 100 mm diameter by 180 mm long.

A1.1 Clean sealable cylindrical plastic bottle and filter patch funnel before use.

A1.2 Remove filter element from machine.

A1.3 Plug clean oil exit hole(s) with suitable rubber stoppers (Fig. A1.1).

A1.4 Place filter element in cylindrical plastic bottle.

A1.5 Pour suitable solvent into plastic bottle until it is approximately half full.

A1.6 Shake container for 3 min manually (Fig. A1.2).

A1.7 Remove filter from bottle—solvent can be used to remove any debris adhering to filter pleats (Fig. A1.3).

A1.8 Put a new filter patch in the holder (Fig. A1.4).

A1.9 Pour contents into the funnel (Fig. A1.4).

A1.10 Ensure waste solvent is captured in an appropriate receptacle and disposed of in accordance with local requirements.

FIG. A1.1 Plug Clean Oil Exit Holes

FIG. A1.2 Shake Container

FIG. A1.3 Remove Filter from Bottle

A1.11 Use solvent bottle to remove:
(a) Any residual debris in container.
(b) Any debris clinging to funnel sides.

A1.12 Remove filter patch and carefully place in receptacle (Fig. A1.5).

A1.13 Label receptacle.

A1.14 Clean bottle and funnel before storage.