



Standard Test Method for Determination of Additive Elements, Wear Metals, and Contaminants in Used Lubricating Oils and Determination of Selected Elements in Base Oils by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES)¹

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This standard has been approved for use by agencies of the Department of Defense.

^{ε1} NOTE—Equation 9 and Paragraph 8.3 were corrected editorially in November 2003.

INTRODUCTION

Costs associated with maintenance due to engine and machine wear can be significant. Therefore, diagnostic methods for determining the condition of engines and other machinery can be important. This test method is intended to quantify, for the purpose of equipment monitoring, the concentration of metals in used lubricating oils. Although the precision statement was determined by analyzing a variety of used oils this test method can, in principle, be used for the analysis of unused oils to provide more complete elemental composition data than Test Methods D 4628, D 4927 or D 4951.

1. Scope*

1.1 This test method covers the determination of additive elements, wear metals, and contaminants in used lubricating oils by inductively coupled plasma atomic emission spectrometry (ICP-AES). The specific elements are listed in Table 1.

1.2 This test method covers the determination of selected elements, listed in Table 1, in re-refined and virgin base oils.

1.3 For analysis of any element using wavelengths below 190 nm, a vacuum or inert-gas optical path is required. The determination of sodium and potassium is not possible on some instruments having a limited spectral range.

1.4 This test method uses oil-soluble metals for calibration and does not purport to quantitatively determine insoluble particulates. Analytical results are particle size dependent, and low results are obtained for particles larger than a few micrometers.²

1.5 Elements present at concentrations above the upper limit of the calibration curves can be determined with additional, appropriate dilutions and with no degradation of precision.

1.6 For elements other than calcium, sulfur, and zinc, the low limits listed in Table 2 and Table 3 were estimated to be ten

times the repeatability standard deviation. For calcium, sulfur, and zinc, the low limits represent the lowest concentrations tested in the interlaboratory study.

1.7 The values stated in SI (metric) units are to be regarded as the standard. The inch-pound units given in parentheses are for information only.

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 and health practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary statements are given in 6.1, 8.2, and 8.4.

2. Referenced Documents

2.1 ASTM Standards:

C 1109 Test Method for Analysis of Aqueous Leachates from Nuclear Waste Materials Using Inductively Coupled Plasma-Atomic Emission Spectrometry³

D 1552 Test Method for Sulfur in Petroleum Products (High-Temperature Method)⁴

D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products⁵

D 4307 Practice for Preparation of Liquid Blends for Use as Analytical Standards⁵

¹ This test method is under the jurisdiction of ASTM Committee D02 on Petroleum Products and Lubricants and is the direct responsibility of Subcommittee D02.03 on Elemental Analysis.

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² Eisentraut, K. J., Newman, R. W., Saba, C. S., Kauffman, R. E., and Rhine, W. E., *Analytical Chemistry*, Vol 56, 1984.

³ *Annual Book of ASTM Standards*, Vol 12.01.

⁴ *Annual Book of ASTM Standards*, Vol 05.01.

⁵ *Annual Book of ASTM Standards*, Vol 05.02.

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

TABLE 1 Elements Determined and Suggested Wavelengths^A

Element	Wavelength, nm
Aluminum	308.22, 396.15, 309.27
Barium	233.53, 455.40, 493.41
Boron	249.77
Calcium	315.89, 317.93, 364.44, 422.67
Chromium	205.55, 267.72
Copper	324.75
Iron	259.94, 238.20
Lead	220.35
Magnesium	279.08, 279.55, 285.21
Manganese	257.61, 293.31, 293.93
Molybdenum	202.03, 281.62
Nickel	231.60, 277.02, 221.65
Phosphorus	177.51, 178.29, 213.62, 214.91, 253.40
Potassium	766.49
Sodium	589.59
Silicon	288.16, 251.61
Silver	328.07
Sulfur	180.73, 182.04, 182.62
Tin	189.99, 242.95
Titanium	337.28, 350.50, 334.94
Vanadium	292.40, 309.31, 310.23, 311.07
Zinc	202.55, 206.20, 313.86, 334.58, 481.05

^A These wavelengths are only suggested and do not represent all possible choices.

TABLE 2 Repeatability

Element	Range, mg/kg	Repeatability, µg/g ^A
Aluminum	6–40	0.71 X ^{0.41}
Barium	0.5–4	0.24 X ^{0.66}
Boron	4–30	0.26 X
Calcium	40–9000	0.0020 X ^{1.4}
Chromium	1–40	0.17 X ^{0.75}
Copper	2–160	0.12 X ^{0.91}
Iron	2–140	0.13 X ^{0.80}
Lead	10–160	1.6 X ^{0.32}
Magnesium	5–1700	0.16 X ^{0.86}
Manganese	5–700	0.010 X ^{1.3}
Molybdenum	5–200	0.29 X ^{0.70}
Nickel	5–40	0.52 X ^{0.49}
Phosphorus	10–1000	1.3 X ^{0.58}
Potassium	40–1200	3.8 X ^{0.33}
Silicon	8–50	1.3 X ^{0.26}
Silver	0.5–50	0.15 X ^{0.83}
Sodium	7–70	0.49 X ^{0.66}
Sulfur	900–6000	0.49 X ^{0.81}
Tin	10–40	2.4 X ^{0.17}
Titanium	5–40	0.54 X ^{0.37}
Vanadium	1–50	0.061 X
Zinc	60–1600	0.15 X ^{0.88}

^A Where: X = mean concentration, µg/g.

D 4628 Test Method for Analysis of Barium, Calcium, Magnesium, and Zinc in Unused Lubricating Oils by Atomic Absorption Spectrometry⁵

D 4927 Test Methods for Elemental Analysis of Lubricant and Additive Components—Barium, Calcium, Phosphorus, Sulfur, and Zinc by Wavelength-Dispersive X-Ray Fluorescence Spectroscopy⁵

D 4951 Test Method for Determination of Additive Elements in Lubricating Oils by Inductively Coupled Plasma Atomic Emission Spectrometry⁵

E 135 Terminology Relating to Analytical Chemistry for Metals, Ores, and Related Materials⁶

TABLE 3 Reproducibility

Element	Range, mg/kg	Reproducibility, µg/g ^A
Aluminum	6–40	3.8 X ^{0.26}
Barium	0.5–4	0.59 X ^{0.92}
Boron	4–30	13 X ^{0.01}
Calcium	40–9000	0.015 X ^{1.3}
Chromium	1–40	0.81 X ^{0.61}
Copper	2–160	0.24 X
Iron	2–140	0.52 X ^{0.80}
Lead	10–160	3.0 X ^{0.36}
Magnesium	5–1700	0.72 X ^{0.77}
Manganese	5–700	0.13 X ^{1.2}
Molybdenum	5–200	0.64 X ^{0.71}
Nickel	5–40	1.5 X ^{0.50}
Phosphorus	10–1000	4.3 X ^{0.50}
Potassium	40–1200	6.6 X ^{0.29}
Silicon	8–50	2.9 X ^{0.39}
Silver	5–50	0.35 X
Sodium	7–70	1.1 X ^{0.71}
Sulfur	900–6000	1.2 X ^{0.75}
Tin	10–40	2.1 X ^{0.62}
Titanium	5–40	2.5 X ^{0.47}
Vanadium	1–50	0.28 X ^{1.1}
Zinc	60–1600	0.083 X ^{1.1}

^A Where: X = mean concentration, µg/g.

3. Terminology

3.1 Definitions:

3.1.1 *emission spectroscopy*—refer to Terminology E 135.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *additive element*—a constituent of a chemical compound that improves the performance of a lubricating oil.

3.2.2 *analyte*—an element whose concentration is being determined.

3.2.3 *Babington-type nebulizer*—a device that generates an aerosol by flowing a liquid over a surface that contains an orifice from which gas flows at a high velocity.

3.2.4 *calibration*—the process by which the relationship between signal intensity and elemental concentration is determined for a specific element analysis.

3.2.5 *calibration curve*—the plot of signal intensity versus elemental concentration using data obtained by making measurements with standards.

3.2.6 *contaminant*—a foreign substance, generally undesirable, introduced into a lubricating oil.

3.2.7 *detection limit*—the concentration of an analyte that results in a signal intensity that is some multiple (typically two) times the standard deviation of the background intensity at the measurement wavelength.

3.2.8 *inductively-coupled plasma (ICP)*—a high-temperature discharge generated by flowing an ionizable gas through a magnetic field induced by a load coil that surrounds the tubes carrying the gas.

3.2.9 *linear response range*—the elemental concentration range over which the calibration curve is a straight line, within the precision of the test method.

3.2.10 *profiling*—a technique that determines the wavelength for which the signal intensity measured for a particular analyte is a maximum.

3.2.11 *radio frequency (RF)*—the range of frequencies between the audio and infrared ranges (3 kHz to 300 GHz).

3.2.12 *wear metal*—an element introduced into the oil by wear of oil-wetted parts.

⁶ Annual Book of ASTM Standards, Vol 03.05.

4. Summary of Test Method

4.1 A weighed portion of a thoroughly homogenized used oil is diluted ten-fold by weight with mixed xylenes or other suitable solvent. Standards are prepared in the same manner. An optional internal standard can be added to the solutions to compensate for variations in test specimen introduction efficiency. The solutions are introduced to the ICP instrument by free aspiration or an optional peristaltic pump. By comparing emission intensities of elements in the test specimen with emission intensities measured with the standards, the concentrations of elements in the test specimen are calculable.

5. Significance and Use

5.1 This test method covers the rapid determination of 22 elements in used lubricating oils and in base oils, and it provides rapid screening of used oils for indications of wear. Test times approximate a few minutes per test specimen, and detectability for most elements is in the low mg/kg range. In addition, this test method covers a wide variety of metals in virgin and re-refined base oils. Twenty-two elements can be determined rapidly, with test times approximating several minutes per test specimen.

5.2 When the predominant source of additive elements in used lubricating oils is the additive package, significant differences between the concentrations of the additive elements and their respective specifications can indicate that the incorrect oil is being used. The concentrations of wear metals can be indicative of abnormal wear if there are baseline concentration data for comparison. A marked increase in boron, sodium, or potassium levels can be indicative of contamination as a result of coolant leakage in the equipment. This test method can be used to monitor equipment condition and define when corrective actions are needed.

5.3 The concentrations of metals in re-refined base oils can be indicative of the efficiency of the re-refining process. This test method can be used to determine if the base oil meets specifications with respect to metal content.

6. Interferences

6.1 *Spectral*—Check all spectral interferences expected from the elements listed in Table 1. Follow the manufacturer's operating guide to develop and apply correction factors to compensate for the interferences. To apply interference corrections, all concentrations must be within the previously established linear response range of each element listed in Table 1. (**Warning**—Correct profiling is important to reveal spectral interferences from high concentrations of additive elements on the spectral lines used for determining wear metals.)

6.1.1 Spectral interferences can usually be avoided by judicious choice of analytical wavelengths. When spectral interferences cannot be avoided, the necessary corrections should be made using the computer software supplied by the instrument manufacturer or the empirical method described below. Details of the empirical method are given in Test

Method C 1109 and by Boumans.⁷ This empirical correction method cannot be used with scanning spectrometer systems when both the analytical and interfering lines cannot be located precisely and reproducibly. With any instrument, the analyst must always be alert to the possible presence of unexpected elements producing interfering spectral lines.

6.1.2 The empirical method of spectral interference correction uses interference correction factors. These factors are determined by analyzing the single-element, high-purity solutions under conditions matching as closely as possible those used for test specimen analysis. Unless plasma conditions can be accurately reproduced from day to day, or for longer periods, interference correction factors found to affect the results significantly must be redetermined each time specimens are analyzed.

6.1.3 Interference correction factors, K_{ia} , are defined as follows: For analyte a , we have:

$$Ca = Ia/Ha \quad (1)$$

where:

Ca = concentration of analyte a ,

Ia = net line intensity (that is, background corrected) of analyte a , and

Ha = sensitivity.

6.1.3.1 Similarly, for an interferent i at the same wavelength:

$$Ci = Ii/Hi \quad (2)$$

where:

Ii = contribution from the peak or wing of the interferent line to the peak intensity of the analyte a .

6.1.3.2 The correction factor, K_{ia} is defined as:

$$K_{ia} = Hi/Ha = Ii/(Ci \times Ha) \quad (3)$$

6.1.3.3 Analysis of high-purity stock solutions with a calibrated instrument gives Ii/Ha , the concentration error that results when analyzing a solution containing an interferent of concentration Ci . Dividing by Ci gives the dimensionless correction factor K_{ia} . To apply these correction factors:

$$Ca, \text{ apparent} = (Ia + Ii)/Ha \quad (4)$$

$$Ca, \text{ apparent} = Ca + Ii/Ha \quad (5)$$

$$Ca = Ca, \text{ apparent} - Ii/Ha \quad (6)$$

$$Ca = Ca, \text{ apparent} - K_{ia} * Ci \quad (7)$$

and, for more than one interferent:

$$Ca = Ca, \text{ apparent} - K_{1a} \times C_1 - K_{2a} \times C_2 - \dots \quad (8)$$

6.1.4 Interference correction factors can be negative if off-peak background correction is employed for element i . A negative K_{ia} can result when an interfering line is encountered at the background correction wavelength rather than at the peak wavelength.

⁷ Boumans, P. W. J. M., "Corrections for Spectral Interferences in Optical Emission Spectrometry with Special Reference to the RF Inductively Coupled Plasma," *Spectrochimica Acta*, 1976, Vol 31B, pp. 147–152.