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Standard Test Method for Evaluation of Automotive Engine Oils for Valve-Train Wear Performance in Cummins ISB Medium-Duty Diesel Engine[1]

This standard is issued under the fixed designation D7484; 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

Any properly equipped laboratory, without outside assistance, can use the procedure described in this test method. However, the ASTM Test Monitoring Center (TMC)[2] provides reference oils and an assessment of the test results obtained on those oils by the laboratory. By these means, the laboratory will know whether its use of the test method gives results statistically similar to those obtained by other laboratories. Furthermore, various agencies require that a laboratory utilize the TMC services in seeking qualification of oils against specifications. For example, the U.S. Army imposes such a requirement in connection with several Army engine lubricating oil specifications.

Accordingly, this test method is written for use by laboratories that utilize the TMC services. Laboratories that choose not to use these services may simply ignore those portions of the test method that refer to the TMC.

This test method may be modified by means of information letters issued by the TMC.[2] In addition, the TMC may issue supplementary memoranda related to the method.

1. Scope

1.1 This test method, commonly referred to as the Cummins ISB Test, covers the utilization of a modern, 5.9 L, diesel engine equipped with exhaust gas recirculation and is used to evaluate oil performance with regard to valve-train wear.

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

1.2.1 *Exceptions*—SI units are provided for all parameters except where there is no direct equivalent such as the units for screw threads, National Pipe Threads/diameters, tubing size, or where there is a sole source of supply equipment specification.

1.2.2 See also A8.1 for clarification; it does not supersede 1.2 and 1.2.1.

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 and health practices and determine the applicability of regulatory limitations prior to use.* See Annex A1 for general safety precautions.

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[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.B0 on Automotive Lubricants.

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[2] Until the next revision of this test method, the ASTM Test Monitoring Center will update changes in the test method by means of information letters. Information letters may be obtained from the ASTM Test Monitoring Center, 6555 Penn Avenue, Pittsburgh, PA 15206-4489. Attention Administrator. This edition incorporates revisions in all information letters through No. 09–01. www.astmtmc.cmu.edu.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D86 Test Method for Distillation of Petroleum Products at Atmospheric Pressure
D93 Test Methods for Flash Point by Pensky-Martens Closed Cup Tester
D97 Test Method for Pour Point of Petroleum Products
D130 Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test
D235 Specification for Mineral Spirits (Petroleum Spirits) (Hydrocarbon Dry Cleaning Solvent)
D445 Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)
D482 Test Method for Ash from Petroleum Products
D524 Test Method for Ramsbottom Carbon Residue of Petroleum Products
D613 Test Method for Cetane Number of Diesel Fuel Oil
D664 Test Method for Acid Number of Petroleum Products by Potentiometric Titration
D976 Test Method for Calculated Cetane Index of Distillate Fuels
D1319 Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption
D2274 Test Method for Oxidation Stability of Distillate Fuel Oil (Accelerated Method)
D2500 Test Method for Cloud Point of Petroleum Products
D2622 Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry
D2709 Test Method for Water and Sediment in Middle Distillate Fuels by Centrifuge
D3338 Test Method for Estimation of Net Heat of Combustion of Aviation Fuels
D4052 Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter
D4175 Terminology Relating to Petroleum, Petroleum Products, and Lubricants
D4294 Test Method for Sulfur in Petroleum and Petroleum Products by Energy Dispersive X-ray Fluorescence Spectrometry
D4739 Test Method for Base Number Determination by Potentiometric Hydrochloric Acid Titration
D5185 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)
D5186 Test Method for Determination of the Aromatic Content and Polynuclear Aromatic Content of Diesel Fuels and Aviation Turbine Fuels By Supercritical Fluid Chromatography
D5453 Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence
D5967 Test Method for Evaluation of Diesel Engine Oils in T-8 Diesel Engine
D6078 Test Method for Evaluating Lubricity of Diesel Fuels by the Scuffing Load Ball-on-Cylinder Lubricity Evaluator (SLBOCLE)
D6838 Test Method for Cummins M11 High Soot Test
D6975 Test Method for Cummins M11 EGR Test
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
E178 Practice for Dealing With Outlying Observations

3. Terminology

3.1 *Definitions:*

3.1.1 *blind reference oil*, *n*—a reference oil, the identity of which is unknown by the test facility.

3.1.1.1 *Discussion*—This is a coded reference oil that is submitted by a source independent from the test facility. **D4175**

3.1.2 *blowby*, *n—in internal combustion engines*, that portion of the combustion products and unburned air/fuel mixture that leaks past piston rings into the engine crankcase during operation.

3.1.3 *calibrate*, *v*—to determine the indication or output of a device (for example, thermometer, manometer, engine) with respect to that of a standard.

3.1.4 *candidate oil*, *n*—an oil that is intended to have the performance characteristics necessary to satisfy a specification and is to be tested against that specification. **D4175**

3.1.5 *crosshead*, *n*—an overhead component, located between the rocker arm and each intake-valve and exhaust-valve pair, that transfers rocker arm travel to the opening and closing of each valve pair.

3.1.5.1 *Discussion*—Each cylinder has two crossheads, one for each pair of intake valves and exhaust valves. **D6838**

3.1.6 *exhaust gas recirculation (EGR)*, *n*—a method by which a portion of engine's exhaust is returned to its combustion chambers via its inlet system. **D6975**

3.1.7 *heavy-duty*, *adj—in internal combustion engine operation*, characterized by average speeds, power output and internal temperatures that are close to the potential maximums. **D4175**

3.1.8 *non-reference oil*, *n*—any oil other than a reference oil, such as a research formulation, commercial oil or candidate oil. **D4175**

3.1.9 *non-standard test*, *n*—a test that is not conducted in conformance with the requirements in the standard test method; such as running in an uncalibrated test stand or using different test equipment, applying different equipment assembly procedures, or using modified operating conditions. **D4175**

3.1.10 *overhead*, *n—in internal combustion engines*, the components of the valve-train located in or above the cylinder head. **D6838**

3.1.11 *reference oil*, *n*—an oil of known performance characteristics, used as a basis for comparison.

[3] 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.

3.1.11.1 *Discussion*—Reference oils are used to calibrate testing facilities, to compare the performance of other oils, or to evaluate other materials (such as seals) that interact with oils. **D4175**

3.1.12 *sludge*, *n—in internal combustion engines*, a deposit, principally composed of insoluble resins and oxidation products from fuel combustion and the lubricant, that does not drain from engine parts but can be removed by wiping with a cloth. **D4175**

3.1.13 *test oil*, *n*—any oil subjected to evaluation in an established procedure. **D4175**

3.1.14 *valve-train*, *n—in internal combustion engines*, the series of components such as valves, crossheads, rocker arms, push rods and camshaft, that open and close the intake and exhaust valves. **D6838**

3.1.15 *wear*, *n*—the loss of material from a surface, generally occurring between two surfaces in relative motion, and resulting from mechanical or chemical action or a combination of both. **D4175**

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *lug*, *v—in internal combustion engine operation*, to run the engine in a condition characterized by a combined mode of relatively low-speed and high-power output, with the potential to cause hesitation.

3.2.2 *ramp*, *v*—to change an engine condition at a prescribed rate when changing from one set of operating conditions to another set of operating conditions.

3.2.2.1 *Discussion*—When ramping the engine speed down to a condition such that the engine lugs, the speed is forced down by increasing the torque in a such a way that the speed comes to idle before zero torque condition is reached.

3.2.3 *tappet*, *n—in internal combustion engines*, a valve-train component, located between the camshaft and push rod, that transfers cam lobe travel to the rocker arm, opening and closing a pair of intake or exhaust valves.

4. Summary of Test Method

4.1 This test method uses a Cummins ISB diesel engine with 5.9 L displacement, equipped with exhaust gas recirculation and featuring an EPA 2004 emissions configuration. Test operation includes a 17 min warm-up, an 80 h break-in, and a 350 h test cycle comprising stages A and B. During stage A the engine is operated with retarded, fuel-injection timing to generate excess soot; during stage B the engine is operated at cyclic conditions to induce valve-train wear.

4.2 Prior to each test, the engine is cleaned and assembled with new, valve-train components. All aspects of the assembly are specified.

4.3 A forced oil drain, an oil sampling, and an oil addition are performed at the end of each 25 h period for the first 100 h of the test. Thereafter, oil samples are taken every 50 h. Oil additions are not made during the last 250 h of the test cycle.

4.4 The test stand is equipped with the appropriate instrumentation to control engine speed, fuel flow and other operating parameters.

4.5 Oil performance is determined by assessing crosshead wear, tappet weight loss and camshaft wear.

5. Significance and Use

5.1 This test method was developed to assess the performance of a heavy-duty engine oil in controlling engine wear under operating conditions selected to accelerate soot production and valve-train wear in a turbocharged and aftercooled four-cycle diesel engine with sliding tappet followers equipped with exhaust gas recirculation hardware.

5.2 The design of the engine used in this test method is representative of many, but not all, modern diesel engines. This factor, along with the accelerated operating conditions, shall be considered when extrapolating test results.

6. Apparatus

6.1 *Test-Engine Configuration*:

6.1.1 *Test Engine*—The Cummins ISB is an in-line, six-cylinder, diesel engine with a displacement of 5.9 L. It is turbocharged, aftercooled, and has an overhead valve configuration. It features a 2004 emissions configuration with electronic control of fuel metering and common rail fuel injection. Obtain the test engine and the engine build parts kit from the Central Parts Distributor (CPD).[4,5] The components of the engine build parts kit are shown in Table A3.1.

6.1.2 *Remote Oil Heat Exchanger and Bypass Plate*—Remove the stock oil heat exchanger from the engine and replace with a bypass plate (part number ISB-OCBP)[4,5] shown in Fig. A4.1. Attach a remote bypass (part number 149-0118-00)[5,6] to the filter head, as shown in Fig. A4.2. The bypass allows control of the oil temperature by directing the oil to flow through a 76 mm × 102 mm dual-pass, remote oil heat exchanger (part number SN16-003-014-004)[5,7] as shown in Fig. A4.3. The oil lines to and from the remote oil heat exchanger and filter head shall not be greater than 1000 mm long and shall be 19.3 mm nominal outer diameter tubing (Aeroquip[8] "-12" or equivalent).

6.1.3 *Oil Pan Modification*—Modify the oil pan as shown in Fig. A4.4.

6.1.4 *Engine Control Module (ECM)*—Obtain the ECM from the CPD.[4,5] Information about the ECM is given in a Cummins publication.[9,10] Use the latest Cummins engineering tools[10] to retard injection timing in order to increase soot generation and overhead wear. Verify that the 2004 EPA calibration is used. Some engine protection protocols have been disabled to ensure that the test is run according to the

[4] This CPD is the sole source of supply of the test engine, engine build parts kit and the ECM known to the committee at this time is Test Engineering, Inc., 12718 Cimarron Path, Suite 102, San Antonio, TX 78249-3423, www.tei-net.com.

[5] If you are aware of alternative suppliers, please provide this information to ASTM. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

[6] The sole source of supply of this bypass known to the committee at this time is W. G. Sourcing, Inc., 2650 Pleasantdale Road #10, Atlanta, GA 30340. www.wgsourcing.net.

[7] The sole source of supply of the remote oil heat exchanger known to the committee at this time is Kinetic Engineering Corporation, 2055 Silber Road, Suite 101, Houston, TX 77055. www.kineticengineerinq.com.

[8] Aeroquip lines are available at a local hose distributors.

[9] *Troubleshooting and Repair Manual ISB, ISB^e, QSB 4.5, QSB 5.9, QSB 6.7, ISC, QSC 8.3, ISL and QSL 9 Engines, CM 850 Electronic Control System Engines*, Bulletin Number 4021416.

[10] Available from local Cummins parts distributors.

procedure. Obtain prior authorization and instructions from Cummins Inc.[11] on how to disable the engine protection protocols and the use of Cummins engineering tools.

6.1.5 *Air Compressor*—The engine-mounted air compressor is not used for this test method. Remove the air compressor and cover the opening by a plate (part number 3954567).[10]

6.1.6 *Engine Inlet Air Heater*—Remove the internal heating elements from the housing of the engine inlet air heater. Remove the lower, factory-installed, electrical terminal. Drill and tap this hole (1⁄8 in. NPT) for the inlet manifold pressure fitting.

6.2 *Test-Stand Configuration*:

6.2.1 *Engine Mounting*—Install the engine so that it is upright and the crankshaft is horizontal, with minimal block distortion. Due to the cyclic nature of the test, a driveline coupling damper is required.[12]

6.2.2 *Intake Air System*—the configuration is shown in Fig. A4.6. Use a cobra elbow (part number 3037625).[4,10] Connect to the cobra elbow using straight, 100 mm diameter tubing with a minimum length of 300 mm. Use an air filter typical of those used in diesel engine testing applications. Install the intake air tube (Fig. A4.6) at the intake of the turbocharger compressor. Construct the system to minimize airflow restriction. Install methods for controlling the intake air temperature and pressure.

NOTE 1—Difficulty in achieving or maintaining intake manifold pressure or intake manifold temperature, or both, could be indicative of insufficient or excessive restriction.

6.2.3 *Aftercooler*—Use a Modine aftercooler for aftercooling. Instructions for obtaining the correct aftercooler are listed in A2.1. An installation photograph is shown in Fig. A4.10.

6.2.4 *Exhaust System*—Install a long-radius, 90°-elbow, exhaust tube (see Fig. A4.11) at the discharge flange of the turbocharger housing, followed by a sufficient length of straight tubing to allow the temperature and pressure sensors to be located 152 mm downstream of the elbow weld seam. Use good engineering practice in establishing the total length and diameter of the tube downstream of the sensors. Install a method of controlling exhaust back pressure.

6.2.5 *Exhaust Gas Recirculation System*—The components for the exhaust gas recirculation system are installed by the manufacturer. Replacement parts are available.[4,10]

6.2.6 *Fuel Supply*—The laboratory fuel supply and filtration systems are not specified. Determine the fuel-consumption rate by measuring the rate of fuel flowing into the day tank. Install a method of controlling the fuel temperature. Ensure the fuel-inlet restriction and return restrictions adhere to the requirements specified in the Cummins Service Manual.[10,13]

6.2.7 *Coolant System*—The coolant system configuration is not specified. A typical configuration consists of a non-ferrous-core heat exchanger, a reservoir (expansion tank), and a temperature-control valve. Pressurize the system by regulating air pressure at the top of the expansion tank. Install a sight glass to detect air entrapment.

NOTE 2—**Caution:** Although the system volume is not specified, an excessively large volume can increase the time required for the engine fluid temperatures to attain specification. A system volume that has been found satisfactory is 35 L or less (including engine).

6.2.7.1 Block the engine thermostat wide open.

6.2.8 *Pressurized Oil-Fill System*—The oil-fill system is not specified. A typical configuration includes an electric pump, a 20 L reservoir and transfer hose.

6.2.9 *External Oil System*—Configure the external oil system according to Fig. A5.1, using an external reservoir with a volume between 4 L and 8 L. Use Viking Pump (model number SG041825)[14] for the external pumps with a nominal pump-motor speed of 1140 r/min. A three-way valve system is permissible and allows the reservoir to be emptied back into the oil pan at the start of Stage B. The location of the three-way valve is not specified (location shown in Fig. A5.1 is for example only).

6.2.9.1 *Oil-Sample Valve Location*—Locate the oil-sample valve on the return line from the remote oil heat exchanger system to the engine. It is recommended that the valve be located as shown in Fig. A4.9.

6.2.9.2 Do not use brass or copper fittings in the external oil system because such metals can influence wear-metals analyses of the used oil.

6.2.10 *Crankcase Aspiration*—Vent the blowby gas at the port located at the left rear of the flywheel housing, as shown in Fig. A4.5. Ensure the vent line proceeds in a downward direction into the collection bucket and that the collection bucket has a minimum volume of 19 L.

6.2.11 *Blowby Rate*—The flow-rate device and system configuration are not specified. Install the system according to good engineering practice and operate the flow-rate device according to the manufacturer's guidelines.

6.3 *System Time Responses*—Table 1 shows the maximum allowable system time responses. Determine system time responses in accordance with the Data Acquisition and Control Automation II (DACA II) Task Force Report.[15]

TABLE 1 Maximum Allowable System Time Responses

Measurement Type	Time Response, s
Speed	2.0
Torque	2.0
Temperature	3.0
Pressure	3.0
Flow	45.0

6.4 *Oil-Sample Containers*—High-density polyethylene containers are recommended for oil samples. (**Warning—** Glass containers may break and may cause injury or exposure to hazardous materials, or both.)

[11] Cummins Inc., 1900 McKinley Avenue, Columbus, IN 47201.

[12] The sole source of supply of the apparatus known to the committee at this time is Vulkan Driveline Coupling (Part Number VKL3415, available from American Vulkan USA, 2525 Dundee Road, Winter Haven, FL 33484. www.vulkanusa.com.

[13] *Troubleshooting and Repair Manual for ISB^e and ISB (Common Rail Fuel System) Series Engines*, Bulletin Number 4021271, June 30, 2004, published by Cummins Inc.

[14] The sole source of supply of the apparatus known to the committee at this time is Viking Pump, Inc., (unit of IDEX Corporation), 406 State St., P.O. Box 8, Cedar Falls, IA 50613-0008. www.vikingpumps.com.

[15] Available from the TMC website: www.astmtmc.cmu.edu.

6.5 *Mass Balance*—Use a balance (electronic or mechanical) to measure the mass of the crossheads and tappets with a minimum indication resolution of 0.1 mg.

7. Engine Fluids and Cleaning Solvents

7.1 *Test Oil*—Approximately 80 L of test oil are required to complete the test.

7.2 *Test Fuel*—Approximately 8000 L of PC-10 (ultra-low-sulfur) diesel fuel[5,16] are required to complete the test. The fuel shall have the properties and tolerances shown in Annex A6.

7.3 *Engine Coolant*—Use 50:50 pre-mixed Fleetguard Compleat PG.[10]

7.4 *Solvents and Cleaners Required*—(**Warning—**Use adequate safety precautions with all solvents and cleaners.)

7.4.1 *Solvent*—Use mineral spirits meeting Specification D235, Type II, Class C requirements for aromatic content (0 to 2 % vol), flash point (61 °C), and color (not darker than +25 on Saybolt Scale or 25 on Pt-Co Scale). Obtain a Certificate of Analysis for each batch of solvent from the supplier. (**Warning—**Combustible. Health hazard.)

7.4.2 *Pentane*—Used for rinsing and cleaning components before measurement. (**Warning—**Flammable. Health hazard.)

7.4.3 *Degreasing Solvent*—EnSolv,[17] a proprietary *n*-propyl bromide based solvent used for cleaning the tappets. (**Warning—**Health hazard.)

8. Preparation of Apparatus

8.1 *Cleaning of Parts*:

8.1.1 *General*—This section describes the preparation of test engine components specific to the Cummins ISB test. Use the Cummins service publications listed in Annex A7 for the preparation of other engine components. Take precautions to prevent rusting of iron components. Additionally, perform any engraving of test parts for identification purposes on non-contact surfaces and follow by the pre-test cleaning as specified in the following sections.

8.1.2 *Engine Block*—The engine block is a parent bore type. This test does not require a complete teardown. Do not clean the internal surfaces and passages of the engine block with solvent.

8.1.3 *Rocker Cover and Oil Pan*—Clean the rocker cover and oil pan with solvent (see Warning in 7.4.1). Use a brush as necessary to remove deposits.

8.1.4 *External Oil System*—Flush the internal surfaces of the oil lines and the external reservoir with solvent. Repeat until the solvent drains clean. Flush solvent through the oil pumps until the solvent drains clean.

8.1.5 *Crosshead Cleaning and Measurement*—Do not handle the crossheads with bare hands; use gloves or plastic-covered tongs.

8.1.5.1 Clean the crossheads with solvent. Use a non-metallic, soft-bristle brush if necessary.

8.1.5.2 Allow the crossheads to air dry (do not use compressed air).

8.1.5.3 Rinse the crossheads in pentane (see Warning in 7.4.2) and allow to air dry (do not use compressed air).

8.1.5.4 Measure each crosshead mass to a tenth of a milligram (xxx.x mg).

8.1.5.5 If an electronic scale is used for mass measurement, use the following procedure:

(1) Demagnetize (degauss) each crosshead prior to measurement.

(2) Measure each crosshead mass twice, using two orientations 90° apart. If the difference between the two mass measurements is greater than 0.2 mg, demagnetize the crosshead again and repeat the measurement process.

8.1.5.6 For laboratories using the TMC services, report the crosshead measurements on the form included in the TMC report package (see 12.1).

8.1.6 *Tappet Cleaning and Measurement*—Do not handle the tappets with bare hands; use Ensolv-compatible gloves or plastic covered tongs.

8.1.6.1 Inspect the tappets for damage and clean with solvent. Use a non-metallic, soft-bristle brush if necessary.

8.1.6.2 Allow the tappets to air dry (do not use compressed air).

8.1.6.3 Rinse the tappets with pentane and allow to air dry (do not use compressed air).

8.1.6.4 Soak the tappets in Ensolv (see Warning in 7.4.3) for 30 min, ensuring that each tappet is completely immersed in the solvent.

8.1.6.5 Allow the tappets to air dry (do not use compressed air).

8.1.6.6 Measure the mass of each tappet, orienting the large, circular, flat surface in an upwards position, to a tenth of a milligram (xxx.x mg).

8.1.6.7 If an electronic scale is used for mass measurement, use the following procedure:

(1) Demagnetize (degauss) each tappet prior to measurement.

(2) Measure the tappet twice, using two orientations, both with the flat face upwards, 90° apart. If the difference between the two mass measurements is greater than 0.2 mg, demagnetize the tappet again and repeat the measurement process.

8.1.6.8 For laboratories using the TMC services, report the tappet measurements on the forms included in the TMC report package (see 12.1).

8.1.7 *Camshaft Cleaning and Measurement*—Clean the camshaft with solvent. Because contamination can adversely affect the wear results, use gloves, not bare hands, to handle the camshaft.

8.1.7.1 Measure the cam lobe heights (heel-to-toe) using a Mitutoyo Snap Gauge (model 201-152),[18] and a Mitutoyo Digital Indicator (model 543-252B).[18]

8.1.7.2 Measure three locations on each lobe: the front edge, the center, and the rear edge. Report the lobe measurement as the average of the three values.

[16] The sole source of supply of the PC-10 test fuel known to the committee at this time is Chevron Phillips Chemical Company LP, 10001 Six Pines Drive, Suite 4036B, The Woodlands, TX 77387-4910. www.cpchem.com.

[17] Ensolv is a registered trademark of, and is available from, Enviro Tech International, Inc., 2525 West LeMoyne Ave., Melrose Park, IL 60160. www.ensolv.com.

[18] The sole source of supply of the apparatus known to the committee at this time is Mitutoyo America Corporation, 965 Corporate Blvd., Aurora, IL 60502. www.mitutoyo.com.

8.1.7.3 For laboratories using the TMC services, report the lobe measurements on the forms included in the TMC report package (see 12.1).

8.2 *Engine Assembly*:

8.2.1 *General*—Except as noted in this section, use the procedures indicated in the Cummins service publications (see Annex A7). Assemble the engine with the components from the ISB Engine Build Parts Kit in numerical order, from front to rear (see Annex A3 for details of the kit).

8.2.2 *Parts Reuse and Replacement*—Except as directed in 8.2.5, engine components may be reused or replaced at the discretion of the laboratory (Cummins Critical Parts List, CPL #8123). The engine block may be reused provided that it meets the serviceability requirements, particularly blowby and cam bore, defined in the Cummins Service Manual.[10]

8.2.3 *Build-Up Oil*—Use the Cummins-branded oil meeting Cummins Engineering Standard 20078.[10]

8.2.4 *Coolant Thermostat*—Lock the engine coolant thermostat open to close off the bypass passage in the engine block.

8.2.5 *New Parts*—The parts listed below are contained in the ISB Engine Build Parts Kit and are not reusable. Prior to use, clean the valve-train parts with solvent. With the exception of the fuel filter, replacement of any part listed below during a test invalidates the test.

8.2.5.1 *Rocker Lever Shafts*.

8.2.5.2 *Rocker Lever Assemblies, Complete with Sockets*.

8.2.5.3 *Tappets*.

8.2.5.4 *Rocker Lever Sockets*.

8.2.5.5 *Push Rods*.

8.2.5.6 *Valve Crossheads*.

8.2.5.7 *Camshaft*.

8.2.5.8 *Test Oil Filter*.

8.2.5.9 *Fuel Filter*—Replacement during a test does not invalidate the test.

8.2.6 The entire engine may be replaced during a reference period provided the engine completes the 80 h, new-engine, break-in cycle specified in 10.1.

8.2.7 Do not replace the cylinder head and power cylinder components during the life of the engine.

8.3 *Operational Measurements*:

8.3.1 *Units and Formats*—See Annex A8. Record operational parameters in accordance with the minimum resolutions given in Table A8.1.

8.3.2 *Instrumentation Calibration*:

8.3.2.1 *Calibration of the Fuel Consumption Rate Measurement System*—Calibrate the fuel consumption rate measurement system before every reference oil test sequence and within nine months after the completion of the last successful calibration test. Volumetric systems shall be temperature-compensated and calibrated against a mass flow device. The flow meter located on the test stand shall indicate within 0.2 % of the calibration standard. The calibration standard shall be traceable to the National Institute for Standards and Technology (NIST).[19]

8.3.2.2 *Calibration of the Temperature Measurement Systems*—Calibrate the temperature measurement systems before every reference oil test sequence and within nine months after the completion of the last successful calibration test. Each temperature measurement system shall indicate within ± 0.5 °C of the laboratory calibration standard. The calibration standard shall be traceable to NIST.[19]

8.3.2.3 *Calibration of the Pressure Measurement Systems*—Calibrate the pressure measurement systems before every reference oil test sequence and within nine months after the completion of the last successful calibration test. The calibration standard shall be traceable to NIST.[19]

8.3.3 *Temperature Measurements*:

8.3.3.1 *Measurement Location*—This section specifies the temperature measurement locations. The measurement equipment is not specified. Install the sensors such that the tip is located midstream of the flow unless otherwise indicated. Follow the guidelines detailed in the DACA II Task Force Report[15] for the accuracy and resolution of the temperature measurement sensors and the complete measurement system.

8.3.3.2 *Coolant-Out Temperature*—Install the sensor as shown in Fig. A4.15(a).

8.3.3.3 *Coolant-In Temperature*—Install the sensor on the right side of the engine on the inlet pipe to the coolant pump intake housing, as shown in Fig. A4.15(b).

8.3.3.4 *Fuel-In Temperature*—Install the sensor in the fuel pump inlet fitting, as shown in Fig. A4.13. The maximum allowable sensor size is 4.8 mm diameter. Install the sensor to the center of the banjo fitting.

8.3.3.5 *Oil Gallery Temperature*—Install the sensor at the metric, straight-thread hole on the left front of the engine, near the ECM, as shown in Fig. A4.12.

8.3.3.6 *Intake Air Temperature*—Install the sensor as shown on Fig. A4.6. Locate the sensor upstream of the cobra elbow 150 mm to 200 mm; ensure that there is straight tubing upstream of the sensor of at least 150 mm in length. Do not install the sensor upstream of the intake air pressure tap.

8.3.3.7 *Intake Manifold Temperature*—Install the sensor at the top of the aluminum snorkel on the air inlet tube, as shown in Fig. A4.7. The insertion depth from the outside surface of the aluminum snorkel shall be 114 mm.

8.3.3.8 *Exhaust Temperature*—Install the sensor as shown in Fig. A4.11.

8.3.3.9 *Oil Sump Temperature*—Install the sensor from the outside pan boss, identified as the Factory/OEM metric-threaded hole, as shown in Fig. A4.4(a), at an insertion depth of 60 mm.

8.3.3.10 *Additional Temperature Measurements*—Monitor any additional temperatures that the laboratory considers beneficial.

NOTE 3—Measurement of the EGR cooler gas inlet and outlet, and coolant inlet and outlet temperatures is recommended. Additional exhaust temperature sensor locations, such as the exhaust ports and pre-turbine (front and rear), are also recommended. The detection of changes in exhaust temperature(s) is an important diagnostic in terms of satisfactory engine operation.

8.3.4 *Pressure Measurements*:

8.3.4.1 *Measurement Location and Equipment*—This section specifies the pressure measurement locations. The measurement equipment is not specified. Follow the guidelines

[19] National Institute for Standards and Technology, www.nist.gov.

detailed in the DACA II Task Force Report[15] for the accuracy and resolution of the pressure measurement sensors and the complete measurement system.

NOTE 4—It is beneficial to install a condensation trap at the lowest elevation of the tubing between the pressure measurement location and the final pressure sensor for crankcase pressure, intake air pressure, and exhaust pressure. Route the tubing to avoid intermediate loops or low spots before and after the condensation trap.

8.3.4.2 *Oil Gallery Pressure*—Measure the pressure at the metric, straight-thread fitting on the left front of the engine, located near the ECM, as shown in Fig. A4.12.

8.3.4.3 *Oil Filter Inlet Pressure*—Measure the pressure at the 1⁄8 in. NPT port located on the remote oil filter assembly, as shown in Fig. A4.9.

8.3.4.4 *Oil Filter Outlet Pressure*—Measure the pressure at the 1⁄8 in. NPT port located on the remote oil filter assembly, as shown in Fig. A4.9.

8.3.4.5 *Intake Manifold Pressure*—Measure the pressure at the 1⁄4 in. NPT port located in the air heater block at the top-front of the intake manifold, as shown in Fig. A4.8.

8.3.4.6 *Crankcase Pressure*—Measure the pressure at the dipstick port located on the left side of the test engine, as shown in Fig. A4.12.

8.3.4.7 *Intake Air Pressure*—Measure the pressure on the intake air tube, as shown in Fig. A4.6. Locate the pressure tap upstream of the cobra elbow 150 mm to 200 mm; ensure that there is straight tubing upstream of the sensor of at least 150 mm in length.

8.3.4.8 *Exhaust Back Pressure*—Measure the static pressure through a hole in the exhaust tube, as shown in Fig. A4.11.

8.3.4.9 *Fuel Pressure*—Measure the pressure on the engine-mounted outlet of the fuel filter, as shown in Fig. A4.14.

8.3.4.10 *Coolant Pressure*—Measure the pressure on top of the expansion tank.

8.3.4.11 *Additional Pressure Measurements*—Monitor any additional pressures considered to be beneficial.

8.3.5 *Flow Rate*:

8.3.5.1 *Flow-Rate Location and Measurement Equipment*—The flow-rate measurement locations are specified in this section. The equipment or type of system for the blowby and fuel flow rates is not specified. Follow the guidelines detailed in the DACA II Task Force Report[15] for the accuracy and resolution of the flow-rate measurement system.

8.3.5.2 *Blowby Flow Rate*—Use engineering judgment and the manufacturer's guidelines concerning the installation and use of the blowby flow-rate measurement device.

8.3.5.3 *Fuel Flow Rate*—Determine the fuel consumption rate by measuring the fuel flowing to the day tank.

9. Engine/Stand Calibration and Non-Reference Oil Tests

NOTE 5—This section is addressed to those laboratories that choose to utilize the services of the TMC[2] in maintaining calibration of the test stand.

9.1 *General*—Calibrate the test engine and the test stand by conducting a test with a blind reference oil.[2] Submit the results to the TMC[2] for determination of acceptance according to the Lubricant Test Monitoring System (LTMS).

9.1.1 Because the Cummins ISB common rail engine is a parent bore block and is not completely rebuilt before each test, an engine is not referenced to a stand. The stand is calibrated for use with different ISB common rail engines as supplied from the CPD.[4]

9.2 *New Test Laboratory/Stand*—A new test laboratory is defined as a laboratory that has never successfully calibrated a test stand. The first test stand at a new laboratory requires two successful calibration tests to establish its first calibration period. All subsequent calibration periods on that stand or any other stand within that laboratory require one successful calibration test.

9.3 *Stand Calibration Period*:

9.3.1 The first two calibration periods on a new test stand are carried out 12 months or 12 operationally valid non-reference oil tests, whichever comes first, from the completion of the last successful calibration test.

9.3.2 All subsequent calibration periods on a test stand are 18 months or 12 operationally valid non-reference oil tests, whichever comes first, from the completion of the last successful calibration test.

9.3.3 *Last Start Date*—A non-reference oil test may be completed provided the warm-up is started prior to the expiration of the calibration period.

9.4 *Stand Modification and Calibration Status*—Modification of the test stand control systems or the conducting of any non-standard test, or both, can invalidate the calibration status. A non-standard test includes any test conducted under a modified procedure, non-procedural hardware, controller set-point modifications, or a combination thereof. Contact the TMC[2] to determine if any such proposed modifications will affect the calibration status.

9.5 *Test Numbering System*:

9.5.1 *General*—The test number has four parts, W-X-Y-Z: W represents the test stand number, X represents the run number for that stand (and has a XXX format), Y represents the eight-digit serial number for that engine, and Z represents the number of test hours completed by that engine block prior to starting the test and has a format XXXX. The value for the number of test hours on the engine, Z, does NOT include the 80 h break-in time (see 10.1) nor does it include time for warm-up and cool-down run times. As an example, test number 64-002-57216596-0350 indicates stand number 64, test number 002 for that stand, engine serial number 57216596, and the engine has 0350 test hours prior to starting this test on engine block 57216596. Every test start (reference oil and non-reference oil) increments X by one.

9.5.2 *Reference Oil Tests*—The sequential stand run number remains unchanged for reruns of aborted, invalid, or unacceptable calibration tests. However, follow the sequential stand run number by a letter suffix (A for the first rerun, B for the second, and so forth).

9.5.3 *Non-Reference Oil Tests*—Do not add a letter suffix to X for aborted or operationally invalid, non-reference oil tests.

9.6 *Reference Oil Test Acceptance*:

9.6.1 Reference oil test acceptance is determined in accordance with the LTMS.[2]

9.7 *Reference Oil Accountability*:

9.7.1 Laboratories shall provide a full accounting of the identification and quantities of all reference oils used. With the exception of the oil analyses required in 11.4, perform no physical or chemical analyses of reference oils without written permission from the TMC. In such an event, include the written confirmation and the data generated in the reference oil test report.

9.7.2 Retain used reference oil samples for 90 days from the End of Test (EOT) date.

9.8 *Donated Reference Oil Test Programs*—The ASTM D02.B0.02 Cummins Surveillance Panel is charged with maintaining effective reference oil test severity and precision monitoring. During times of new parts introductions, new or re-blended reference oil additions, and procedural revisions, it may be necessary to evaluate the possible effects on severity and precision levels. The Surveillance Panel may choose to conduct a program of donated reference oil tests in those laboratories participating in the monitoring system, in order to quantify the effect of a particular change on severity and precision. Typically, the Surveillance Panel requests its panel members to volunteer enough reference oil test results to create a robust data set. Broad laboratory participation is needed to provide a representative sampling of the industry. To ensure the quality of the data obtained, donated tests are conducted on calibrated test stands. The Surveillance Panel shall arrange an appropriate number of donated tests and ensure completion of the test program in a timely manner.

9.9 *Adjustments to Reference Oil Calibration Periods*:

9.9.1 *Procedural Deviations*—On occasions when a laboratory becomes aware of a significant deviation from the test method, such as might arise during an in-house review or a TMC inspection, the laboratory and the TMC shall agree on an appropriate course of action to remedy the deviation. This action may include the shortening of existing reference oil calibration periods.

9.9.2 *Parts and Fuel Shortages*—Under special circumstances, such as industrywide parts or fuel shortages, the Surveillance Panel may direct the TMC to extend the time intervals between reference oil tests. These extensions shall not exceed one regular calibration period.

9.9.3 *Reference Oil Test Data Flow*—To ensure continuous severity and precision monitoring, calibration tests are conducted periodically throughout the year. There may be occasions when laboratories conduct a large portion of calibration tests in a short period of time. This could result in an unacceptably large time frame when very few calibration tests are conducted. The TMC can shorten or extend calibration periods as needed to provide a consistent flow of reference oil test data. Adjustments to calibration periods are made such that laboratories incur no net loss (or gain) in calibration status.

9.9.4 *Special Use of the Reference Oil Calibration System*—The Surveillance Panel has the option to use the reference oil system to evaluate changes that have potential impact on test severity and precision. This option is only taken when a program of donated tests is not feasible. The Surveillance Panel and the TMC shall develop a detailed plan for the test program. This plan requires all reference oil tests in the program to be completed as close to the same time as possible, so that no laboratory/stand calibration is left in an excessively long pending status. In order to maintain the integrity of the reference oil monitoring system, each reference oil test is conducted so as to be interpretable for stand calibration. To facilitate the required test scheduling, the Surveillance Panel may direct the TMC to lengthen and shorten reference oil calibration periods within laboratories such that the laboratories incur no net loss (or gain) in calibration status.

TABLE 2 15 min Break-in Cycle

Step	Torque, N·m	Speed, r/min	Time, s
1	0 %[A]	800	144
2	800[B]	1600	36
3	800[B]	2600	360
4	0 %[A]	3000	36
5	800[B]	2600	144
6	800[B]	Ramp down from 2600 to 1600	36
7	800[B,C]	1600	108
8	0 %[A]	3000	36

[A] No excitation on the dynamometer.
[B] Nominal.
[C] During step 7, turbocharger surge conditions may occur in the induction system requiring torque to be reduced by about (3 to 8) %.

10. Test Procedure

10.1 *New Engine Break-In*—The engine break-in procedure consists of a sequence of 15 min cycles run for a total of 80 h (see Table 2). With the exception of Step 6 in Table 2, perform changes in torque and speed at a rapid rate. This break-in cycle is only required for first-time use engines. The original equipment (OE) oil cooler may be left installed as received; the OE fuel filter and peripherals are also allowed.

10.1.1 *Oil Charge for Break-In*—Install a non-test oil filter (part number LF3970) and pressure charge the engine with 14.5 kg of Cummins branded CES 20078 oil.[10] This amount includes oil in the filter.

10.1.2 *Break-In Cycle*—Run the break-in cycle, as detailed in Table 2, for 80 h.

10.1.3 *Post Break-In*—Drain the break-in oil. The engine may now be used for testing and is ready to be equipped and assembled as detailed in sections 6.1 and 8.

10.2 *Pretest Procedure*:

10.2.1 *Pretest Oil Charge*—Install a new, non-test, oil filter (part number LF3970[10]) and pressure charge the engine with 14.5 kg of test oil. This amount includes oil in the filter.

10.2.2 *Engine Start-up*—For the first start-up with new test parts, start the engine and idle (no torque) for no more than 10 s. Within 5 s, ramp the engine to 3000 r/min and no torque and hold those conditions to break in the cam and tappets for 30 s.

10.2.2.1 Perform this step only once, at the first start-up for new test parts. Do not use it for subsequent start-ups on the same set of test parts.

10.2.2.2 For all subsequent start-ups on the same set of test parts, proceed directly to the 1300 r/min and no torque conditions of the engine warm-up as directed in 10.2.3.1.

10.2.3 *Engine Warm-Up Procedure*—Perform all engine start-ups as directed in this section, changing set points in a step-wise fashion.

TABLE 3 Test Conditions

Test Parameter	Stage A	Stage B
Time, h	100	250^A
Engine speed, r/min	1600 ± 10	Varies
Torque, N·m	Resultant	Varies
Fuel Rate, kg/h	20.0 ± 0.3	Varies
Coolant-out temperature, °C	99 ± 3	99 ± 3^B
Coolant pressure, kPa	99 to 107	99 to 107
Intake manifold pressure, kPa	Resultant	Varies
Intake manifold temperature, °C	68 ± 2	68 ± 5^B
Inlet-air temperature, °C	25 to 35	25 to 35^B
Turbine-inlet temperature, °C	Resultant	Varies
Oil-pan temperature, °C	110 ± 2	110 ± 2^B
Oil pressure, kPa	Resultant	Varies
Intake-air restriction, kPa	1 to 3	0 to 4
Exhaust back pressure, kPa	6 to 8	4 max at Step 2 of Stage B
Fuel temperature, °C	40 ± 2	40 ± 2
Fuel lift pump pressure, kPa	Record	Record

^{A} Stage B length is determined by test time. For a test to be operationally valid, a minimum of 32 000 cycles shall be completed within the 250 h of Stage B.
^{B} Intended set point, but may vary due to cyclic conditions.

10.2.3.1 Run the engine at 1300 r/min and no torque for 2 min. (If the start-up is for Stage A, start the auxiliary oil pump.)

10.2.3.2 Increase torque to 200 N·m for 5 min.

10.2.3.3 Increase torque to 400 N·m for 5 min.

10.2.3.4 Increase speed to 2600 r/min and torque to 600 N·m for 5 min.

10.2.4 *Pretest Oil Flush*—Operate the engine at 1600 r/min and 440 N·m for 15 min. Shutdown the engine as directed in 10.2.5 and drain the oil for 30 min.

10.2.4.1 Replace the non-test oil filter with another non-test filter. Repeat the pretest oil charge (10.2.1) and the engine warm-up (10.2.3), and operate the 1600 r/min and 440 N·m flush condition for 15 min. Shutdown the engine (10.2.5) and drain the oil for 30 min.

10.2.4.2 Replace the oil filter with a test filter (part number 3937736, which is part of the ISB Engine Build Parts Kit listed in Annex A3).

10.2.5 *Engine Shutdown*—Perform all non-emergency shutdowns as directed in this section, changing set points in a step-wise fashion.

10.2.5.1 *From Stage A Test Condition* (see Table 3):

(1) Decrease engine speed to 1300 r/min and torque to 440 N·m for 1 min.

(2) Decrease torque to 200 N·m for 1 min.

(3) Run engine at low idle and no torque for 2 min.

10.2.5.2 *From Stage B Test Condition* (see Table 3):

(1) Run engine at 1300 r/min and 200 N·m for 2 min.

(2) Run engine at low idle and no torque for 2 min.

10.3 *350 h, Two-Stage, Test Cycle*:

10.3.1 *Test-Oil Charge*—Pressure charge the engine with 14.5 kg of test oil. This amount includes oil in the filter.

10.3.2 *Test Conditions*—Warm-up the engine as directed in 10.2.3 and run the test conditions shown in Tables 3 and 4 for 350 h. At the conclusion of the 350 h test, shut down the engine as directed in 10.2.5.

10.3.3 *Oil Samples*—Every 25 h from (0 to 100) h, and every 50 h from 150 h to end-of-test, take 120 mL oil samples from the sample valve (see Fig. A4.9). A purge (120 mL for Stage A and 30 mL for Stage B) shall be taken prior to taking the sample. During Stage A, return the purge to the auxiliary oil reservoir; during Stage B, discard the purge. Take oil samples prior to forced additions.

10.3.4 *Stage A Details*:

10.3.4.1 Run at retarded timing (–16° maximum) to generate (3.25 ± 0.25) % soot at 100 h. Use Cummins engineering tool[10] to change final timing as indicated on engineering tool display.

10.3.4.2 *Oil Addition/Drain*—Initially establish the full mark as the oil scale weight after 4 h of running Stage A. At (25, 50, 75, and 100) h, drain a sufficient amount of oil to obtain an oil weight that is below the full mark by 1000 g. Add back 1000 g of fresh test oil. For any 25 h period in which the oil weight is already below the full mark by more than 1000 g, do not perform the force drain.

10.3.4.3 Immediately after the 100 h oil addition, close the auxiliary oil system suction valve, allow the auxiliary oil pumps to empty the external oil reservoir and force the oil into the oil pan. When the external reservoir is empty, close the external oil valves and turn off the external oil pumps. (Perform these actions in the final minutes while the engine is still operating at Stage A conditions.)

10.3.4.4 *Data Collection Minima for Stage A*—Take snapshot readings of all operational data every 6 min.

10.3.5 *Stage B Details*:

10.3.5.1 Table 4 describes the Stage B test cycle. The maximum duration of the cycle is 28 s. Repeat this cycle for 250 h.

10.3.5.2 Return timing to default (native timing) using the Cummins engineering tool.

10.3.5.3 No fresh-oil replacement or additions are allowed throughout Stage B.

10.3.5.4 Stage B length is based on test time. Complete a minimum of 32 000 cycles for the test to be valid. The cycle counter advances at the completion of the last, low-idle step.

10.3.5.5 *Data-Collection Minima for Stage B*—At least every 12 cycles, capture snapshot of all data 1 s before the end of the rated speed stage (5 s into step 2 of Table 4). Every 1000 cycles take a minimum of two consecutive full-cycle traces of speed and torque at 10 Hz.

10.4 *Post-Test*:

10.4.1 Drain the test oil for 30 min. Remove the test oil filter.

10.4.2 Install a non-test oil filter. Charge the engine with 14.5 kg of Cummins-branded CES 20078 oil.[10] Circulate the oil through the engine using an oil flush cart for 15 min. At the end of 15 min, drain all the flush oil.

10.4.3 Remove, clean, and measure test parts as directed in 8.1.

11. Calculations, Ratings, and Test Validity

11.1 *Crosshead-Mass Loss*:

11.1.1 Use the procedure in 8.1.5 to determine and report the pre-test and EOT mass of the individual crossheads.

11.1.2 Separate the crossheads into intake and exhaust groups.

TABLE 4 Stage B, 28 s, Test Cycle

Step	Step Timer, s	Accumulated Time, s	Operation	Engine Throttle Position, %	Speed, r/min	Torque,[A] N·m
0	0	0	Idle	0	750 to 850	No torque (zero excitation)
1	2.5	2.5	Accelerate to step 2 conditions	100	Ramp up	Ramp up
2	6.0	8.5	Rated speed	100	2600[B]	800
3	2.0	10.5	Lug[C] to step 4 conditions	0	Ramp down	Ramp down
4	1.0	11.5	Idle	0	750 to 850	No torque (zero excitation)
5	2.5	14.0	Accelerate to speed & within 1.5 s	75[D]	Peak 1600 to 1750 for min 0.5 s	550 to 750
6	2.0	16.0	Lug[C] to step 7 conditions	0	Ramp down	Ramp down
7	1.0	17.0	Low Idle	0	750 to 850	No torque (zero excitation)
8	2.5	19.5	Accelerate to speed & torque within 1.5 s	75[D]	Peak 1600 to 1750 for min 0.5 s	550 to 750
9	2.0	21.5	Lug[C] to step 10 conditions	0	Ramp down	Ramp down
10	1.0	22.5	Idle	0	750 to 850	No torque (zero excitation)
11	2.5	25.0	Accelerate to speed & torque within 1.5 s	75[D]	Peak 1600 to 1750 for min 0.5 s	550 to 750
12	2.0	27.0	Lug[C] to step 13 conditions	0	Ramp down	Ramp down
13	1.0	28.0	Idle	0	750 to 850	No torque (zero excitation)

[A] This is the nominally observed torque.
[B] Engine speed average (over 6 s) shall be (2600 ± 50) r/min. An initial overshoot between (2650 and 2800) r/min is allowed.
[C] Engine speed shall come to idle before reaching a no torque condition, i.e., the torque forces the speed down.
[D] Approximate throttle position to reach specified speed and torque.

11.1.3 Calculate and report the mass loss for each crosshead as pre-test mass minus EOT mass. Calculate and report the average, crosshead-mass loss for both the intake and exhaust groups.

11.1.4 Use Practice E178, two-sided test at a 95 % significance level, to determine if any crosshead-mass loss values are outliers (keeping the intake and exhaust groups separate). Report the outlier-screened, average crosshead-mass loss values for both the intake and exhaust groups. If no outliers are identified, these values will be the same as the values calculated in 11.1.3.

11.1.5 Calculate the overall, outlier-screened, average, crosshead-mass loss as follows:

$$CAWL = (OACWLI + OACWLE)/2 \quad (1)$$

where:

CAWL = outlier-screened, average, crosshead-mass loss, mg,
OACWLI = outlier-screened, average, intake crosshead-mass loss (11.1.4), mg, and
OACWLE = outlier-screened, average, exhaust crosshead-mass loss (11.1.4), mg.

11.1.6 Calculate and report the average, crosshead-mass loss, adjusted to 3.50 % soot mass as follows:

$$ACWL = CAWL - 1.3(TGAAVG - 3.50) \quad (2)$$

where:

ACWL = average, crosshead-mass loss adjusted to 3.50 % soot mass, mg, and
TGAAVG = average of the nine Thermal Gravimetric Analysis (TGA) soot-concentration measurements from 25 h to 350 h (see 11.4 and Table A9.1), mass %.

11.2 *Tappet-Mass Loss*:

11.2.1 Use the procedure in 8.1.6 to determine and report the pre-test and EOT mass of the individual tappets.

11.2.2 Separate the tappets into intake and exhaust groups.

11.2.3 Calculate and report the mass loss for each tappet as pre-test mass minus EOT mass. Calculate and report the average, tappet-mass loss for both the intake and exhaust groups.

11.2.4 Use Practice E178, two-sided test at a 95 % significance level, to determine if any tappet-mass loss values are outliers (keeping the intake and exhaust groups separate). Report the outlier-screened, average, tappet-mass loss values for both the intake and exhaust groups. If no outliers are identified, these values will be the same as the values calculated in 11.2.3.

11.2.5 Calculate the overall, outlier-screened, average, tappet-mass loss as follows:

$$TWL = (OATWLI + OATWLE)/2 \quad (3)$$

where:

TWL = outlier- screened, average, tappet-mass loss, mg,
OATWLI = outlier-screened, average, intake tappet-mass loss (11.2.4), mg, and
OATWLE = outlier-screened, average, exhaust tappet-mass loss (11.2.4), mg.

11.2.6 Calculate and report the average, tappet-mass loss (soot-adjusted) as follows:

11.2.6.1 For all tests starting on or before January 24, 2007:

$$ATWL = TWL - 76(TGAAVG - 3.50) \quad (4)$$

where:

ATWL = average, tappet-mass loss (soot adjusted), mg,
TWL = outlier-screened, average, tappet-mass loss, mg, and
TGAAVG = average of the nine soot mass measurements from 25 h to 350 h (see 11.4 and Table A9.1), percent.

11.2.6.2 For all tests starting on or after January 25, 2007: