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.

Designation: D7468 – 22

Standard Test Method for Cummins ISM Test[1]

This standard is issued under the fixed designation D7468; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 The test method covers a heavy-duty diesel engine test procedure conducted under high soot conditions to evaluate oil performance with regard to valve train wear, top ring wear, sludge deposits, and oil filter plugging in an EGR environment. This test method is commonly referred to as the Cummins ISM Test.[2]

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 *Exception*—The only exception is where there is no direct SI equivalent such as screw threads, national pipe threads/diameters, tubing sizes, or where there is a sole source of supply equipment specification.

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.* See Annex A1 for general safety precautions.

1.4 *Table of Contents:*

[1] This test method is under the jurisdiction of ASTM Committee D02 on Petroleum Products, Liquid Fuels, 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 this test method by means of Information Letters. Information letters may be obtained from the ASTM Test Monitoring Center, 203 Armstrong Drive, Freeport, PA 16229, Attention: Director. This edition incorporates revisions in all information letters through No. 22-1.

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

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1.5 *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:*[3]

D86 Test Method for Distillation of Petroleum Products and Liquid Fuels 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)

D287 Test Method for API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method)

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 and Liquid Fuels

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

D4052 Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter

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

D4294 Test Method for Sulfur in Petroleum and Petroleum Products by Energy Dispersive X-ray Fluorescence Spectrometry

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[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.

D4485 Specification for Performance of Active API Service Category Engine Oils
D4737 Test Method for Calculated Cetane Index by Four Variable Equation
D4739 Test Method for Base Number Determination by Potentiometric Hydrochloric Acid Titration
D5185 Test Method for Multielement Determination of Used and Unused Lubricating Oils and Base Oils by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES)
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
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
E178 Practice for Dealing With Outlying Observations

2.2 *Other ASTM Document:*
ASTM Deposit Rating Manual 20 (Formerly CRC Manual 20)[4]

2.3 *National Archives and Records Administration:*
Code of Federal Regulations Title 40 Part 86.310-79[5]

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. **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 (e.g., thermometer, manometer, engine) with respect to that of a standard.

3.1.4 *exhaust gas recirculation (EGR), n*—a method by which a portion of the engine exhaust is returned to the combustion chambers through the intake system.

3.1.5 *heavy-duty, adj—in internal combustion engine operation*, characterized by average speeds, power output, and internal temperatures that are close to the potential maximum. **D4485**

3.1.6 *heavy-duty engine, n—in internal combustion engine types*, one that is designed to allow operation continuously at or close to its peak output.

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

3.1.8 *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 non-calibrated test stand or using different test equipment, applying different equipment assembly procedures, or using modified operating conditions. **D4175**

3.1.9 *reference oil, n*—an oil of known performance characteristics, used as a basis for comparison. **D4485**

3.1.10 *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**

3.1.11 *test oil, n*—any oil subjected to evaluation in an established procedure. **D5967**

3.1.12 *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.

3.1.13 *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 *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.

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

3.2.2 *de-rate protocols, n*—protocols in the engine control module that cause the engine to reduce power output when certain operating parameters are exceeded.

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

3.2.4 *overfuel, v*—to cause the fuel flow to exceed the standard production setting.

4. Summary of Test Method

4.1 This test method uses a Cummins ISM 500 diesel engine with a specially modified engine block. Test operation includes a 25 min warm-up, a 2 h break-in, and 200 h in four 50 h stages. During stages A and C the engine is operated with retarded fuel injection timing and is overfueled to generate excess soot. During stages B and D the engine is operated at conditions to increase valve train wear.

4.2 Prior to each test, the engine is cleaned and assembled with new cylinder liners, pistons, piston rings and overhead valve train components. All aspects of the assembly are specified.

4.3 A forced oil drain, an oil sample and an oil addition, equivalent to an oil consumption of 0.064 g/MJ, is performed at the end of each 25 h period.

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

[4] For stock #TMCMNL20, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org.

[5] Available from Superintendent of Documents, Attn: New Orders, P.O. Box 371954, Pittsburgh, PA 15250-7954. Charge orders may be telephoned to the Government Printing Office order desk.

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4.5 Oil performance is determined by assessing crosshead wear, top ring mass loss, injector adjusting screw mass loss, sludge deposits, and oil filter plugging.

5. Significance and Use

5.1 This test method was developed to assess the performance of an engine oil to control engine wear and deposits under heavy-duty operating conditions selected to accelerate soot generation, valve train wear, and deposit formation in a turbocharged, aftercooled four-stroke-cycle diesel engine equipped with exhaust gas recirculation hardware.

5.2 This test method can be used for engine oil specification acceptance when all details of this test method are in compliance. Applicable engine oil service categories are included in Specification D4485.

5.3 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 needs to be considered when extrapolating test results.

6. Apparatus

6.1 *Test Engine Configuration:*

6.1.1 *Test Engine*—The Cummins ISM 500 is an in-line six-cylinder heavy-duty diesel engine with 11 L of displacement and is turbocharged and aftercooled. The engine has an overhead valve configuration and EGR hardware. It features a 2002 emissions configuration with electronic control of fuel metering and fuel injection timing. Obtain the test engine and the engine build parts kit from the central parts distributor (CPD).[6] The components of the engine build parts kit are shown in Table A3.1. Non-kit parts are shown in Table A3.2.

6.1.2 *Oil Heat Exchanger, Adapter Blocks, and Block-off Plate*—The oil heat exchanger is relocated from the stock position with the use of adapter blocks as shown in Fig. A4.1.[7] Install an oil cooler block-off plate on the back of the coolant thermostat housing (Fig. A4.1). Control the oil temperature by directing process water through the oil heat exchanger (Fig. A4.1).

6.1.3 *Oil Filter Head Modification*—Modify the oil filter head by plugging the filter bypass return to sump line and the engine oil thermostat (Fig. A4.2). Block the thermostat passage to route all of the engine oil into the oil cooler. The casting shown in Fig. A4.2 is available from Cummins in assembly P/N 3895946.

6.1.4 *Oil Pan Modification*—Modify the oil pan as shown in Fig. A4.3.[7]

6.1.5 *Engine Control Module (ECM)*—Obtain the ECM from the CPD.[6] The ECM programming is modified, using the Cummins engineering tool, to provide retarded injection timing, increasing soot generation and valve and injector train wear. Some engine protection protocols are disabled to allow test conditions to be attained. Before a test lab can obtain the Cummins engineering tool and instructions describing how to disable the engine protection protocols, the test lab shall have a signed confidentiality agreement in place with Cummins. Contact the TMC to obtain the identification of the current ECM calibration file and current communication protocol file.[8] Obtain calibration and communication protocol files from Cummins.

6.1.6 *Engine Position Sensor*—When using the CM870 ECM, disable the secondary engine position sensor measurement coil by cutting the two outside wires colored red and black. The red and black wires are labeled A and D respectively on the engine position sensor plug (Fig. A4.4).

6.1.7 *Intake Manifold Temperature Sensor*—Substitute a 1.8 kΩ resistor or potentiometer for the intake manifold temperature sensor. The Cummins engineering tool shall indicate 65.6 °C (150 °F) after the intake manifold temperature sensor has been replaced with the appropriate resistance.

6.1.8 *Barometric Pressure Sensor*—Disconnect the barometric pressure sensor. Replace the sensor with a 200 Ω resistor or potentiometer from power to ground (pins 1 and 2) and an 800 Ω resistor or potentiometer from signal to ground (pins 2 and 3). The Cummins engineering tool shall indicate 101.2 kPa (29.9 in. Hg) after the barometric pressure sensor has been replaced with the appropriate resistance.

6.1.9 *Turbocharger Controller*—Supply nominal 550 kPa air pressure to the turbocharger controller.

6.1.10 *Power Supply Voltage*—The nominal power supply (battery) voltage is 12 Vdc, as displayed on the Cummins engineering tool.

6.1.11 *Air Compressor and Fuel Pump*—The engine-mounted air compressor is not used for this test method. Remove the air compressor and install the fuel injection pump in its place (Fig. A4.5). The fuel injection pump is driven with Cummins coupling P/N 208755.[9]

6.1.12 *Engine Block Preparation*—Verify the oil capacitors have been disabled. If the oil capacitors have not been disabled, use the following procedure.

6.1.12.1 Modify a nominal 25 mm hole saw by replacing the drill bit from the drive arbor with a rod protruding from the saw cutting surface (Fig. A4.16). The rod prevents damage to the engine block as the hole saw breaks through the block.

6.1.12.2 Insert the modified hole saw arbor into the cast oil drain back hole in the bottom of the capacitor.

6.1.12.3 Saw through the bottom of the capacitor wall (Fig. A4.17) and remove the core produced by the hole saw.

6.1.12.4 Remove all burrs and debris from the area around the hole.

6.2 *Test Stand Configuration:*

6.2.1 *Engine Mounting*—Install the engine so that it is upright and the crankshaft is horizontal.

6.2.1.1 Configure the engine mounting hardware to minimize block distortion when the engine is fastened to the mounts. Excessive block distortion may influence test results.

6.2.2 *Intake Air System*—With the exception of the intake air tube, the intake air system is not specified. A typical

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[6] Available from Test Engineering Inc., 12758 Cimmaron Path, Suite 102, San Antonio, TX 78249-3417.

[7] Available from Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228.

[8] Available from the ASTM Test Monitoring Center, 203 Armstrong Drive, Freeport, PA 16229, Attention: Director.

[9] Available from a Cummins parts distributor.

TABLE 1 200 h Test Sequence

Parameter	Unit	Stage A	Stage B	Stage C	Stage D
Stage Length	h	50	50	50	50
Speed	r/min	1800 ± 5	1600 ± 5	1800 ± 5	1600 ± 5
Power	kW	record	record	record	record
Torque (typical)[A]	N·m	1220	1830	1220	1830
Fuel Flow	kg/h	58 ± 1	64.4 ± 1	58 ± 1	64.4 ± 1
Intake Manifold Temp.	°C	80	65.5	80	65.5
Blowby Flow	L/min	record	record	record	record
Coolant Out Temp.	°C	65.5 ± 2	65.5 ± 2	65.5 ± 2	65.5 ± 2
Coolant In Temp.	°C	record	record	record	record
Coolant Delta Temp.	°C	record	record	record	record
Fuel In Temp.	°C	40 ± 2	40 ± 2	40 ± 2	40 ± 2
Oil Gallery Temp.	°C	115 ± 2	115 ± 2	115 ± 2	115 ± 2
Turbo Inlet Temp.	°C	record	record	record	record
Intake Manifold Press.	kPa abs.	≥ 300	≥ 320	≥ 300	≥ 320
Exhaust Temp.	°C	record	record	record	record
Fuel Pressure	kPa	record	record	record	record
Oil Gallery Pressure	kPa	record	record	record	record
Oil Filter Delta Press.	kPa	record	record	record	record
Coolant System Press.[B]	kPa	99-107	99-107	99-107	99-107
Exhaust Press.	kPa abs.	107 ± 1	107 ± 1	107 ± 1	107 ± 1
Crankcase Press.	kPa	record	record	record	record
Inlet Air Press.	kPa abs.	record	record	record	record
Intake CO_2	%	0.97-1.09	0.97-1.09	0.97-1.09	0.97-1.09

[A] At standard atmospheric temperature and pressure.
[B] Measure the coolant pressure on the top of the expansion tank.

configuration is shown in Fig. X1.1. The air filter should be typical of air filters used for engines in heavy-duty applications. Install the intake air tube (Fig. A4.6) at the intake of the turbocharger compressor. The system shall allow control of applicable parameters listed in Table 1.

NOTE 1—Difficulty in achieving or maintaining intake manifold pressure or intake manifold temperature, or both, may 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.

6.2.4 *Exhaust System*—Install the exhaust tube (Fig. A4.7) at the discharge flange of the turbocharger turbine housing. The piping downstream of the exhaust tube is not specified. A method to control exhaust pressure is required.

6.2.5 *Exhaust Gas Recirculation System*—The EGR system is supplied with the engine. Modify the EGR valve by drilling vent holes in the actuator case (Fig. A4.18). Provide 138 kPa air to the EGR valve actuator. Vent the coolant from the coolant vent block to the bottom of the expansion tank as shown in Fig. X1.3.

6.2.6 *Fuel System*—The fuel supply and filtration system is not specified. A typical configuration is shown in Fig. X1.2. The fuel consumption rate is determined by measuring the rate of fuel flowing into the day tank. A method to control the fuel temperature is required.

6.2.7 *Coolant System*—The system configuration is not specified. A typical configuration consists of a non-ferrous core heat exchanger, a reservoir (expansion tank), a temperature control valve, and a vent line from the coolant vent block on the engine to the bottom of the expansion tank as shown in Fig. X1.3. Pressurize the system by regulating air pressure at the top of the expansion tank. The system should have a sight glass to detect air entrapment.

TABLE 2 Maximum Allowable System Time Responses

Measurement	Time Response (s)
Speed	2.0
Temperature	3.0
Pressure	3.0
Flow	45

6.2.7.1 Although the system volume is not specified, an excessively large volume may increase the time required for the engine fluid temperatures to attain specification. A system volume of 45 L or less, including the volume contained in the engine, has proven satisfactory.

6.2.8 *Pressurized Oil Fill System*—The oil fill system is not specified. A typical configuration includes an electric pump, a 50 L reservoir, and a transfer hose. The location for the pressurized fill is located on the filter head (Fig. A4.2).

6.2.9 *External Oil System*—Configure the external oil system in accordance with Fig. A5.1. Use a (10 to 13) L container for the external oil reservoir. Use Viking Pump model number SG053514. Nominal pump motor speed is 1725 r/min.

6.2.9.1 *Oil Sample Valve Location*—Locate the oil sample valve on the return line from the external oil system to the engine. Locate the valve as close to the return pump as possible (Fig. A5.1).

6.2.9.2 *Unacceptable Oil System Materials*—Do not use brass or copper fittings because they can influence used oil wear metals analyses in the external oil system.

6.2.10 *Crankcase Aspiration*—Vent the blowby gas at the port located on the left side of the valve cover (Fig. A4.8). Route the vent line downward from the valve cover port to the blowby canister. The line shall be between (1.2 and 1.8) m in length and 1.5875 cm minimum inside diameter.

6.2.11 *Blowby Rate*—The flowrate measurement device is not specified. The blowby canister shall be 35 L minimum in volume. The outlet of the blowby canister to the flowrate device shall be 3.175 cm minimum inside diameter. The hose connecting the blowby canister to the flowrate device shall be 3.81 cm minimum inside diameter. The length of this hose is not specified.

6.3 *System Time Responses*—The maximum allowable system time responses are shown in Table 2. Determine system time responses in accordance with the Data Acquisition and Control Automation II (DACA II) Task Force Report.[8]

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.)

6.5 *Mass Balance*—A balance is required to measure the mass of the crossheads, rod bearings, injector adjusting screws, and piston rings. An electronic or mechanical balance may be utilized. The balance shall have a minimum display resolution of 0.1 mg.

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7. Engine and Cleaning Fluids

7.1 *Test Oil*—Approximately 75 L of test oil is required to complete the test.

7.2 *Test Fuel*—Approximately 15 500 L of Chevron Phillips PC-9-HS diesel fuel[10] is required to complete the test. Fuel property tolerances are shown in the “PC-9-HS Fuel Specification” section of the “TMC-Monitored Test Fuel Specifications” document maintained by the TMC.[11]

7.3 *Engine Coolant*—Use premixed 50/50 Fleetguard Compleat PG.[9]

7.4 *Pentane*—(**Warning—**Flammable. Health hazard.)

7.5 *Solvent*—Use a solvent which meets Specification D235 for mineral spirits, Type II, Class C for Aromatic Content (0-2 % vol), Flash Point (61 °C, min), 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. Use adequate safety precautions with all solvents and cleaners.)

8. Preparation of Apparatus

8.1 *Cleaning of Parts:*

8.1.1 *General*—The preparation of test engine components specific to the Cummins ISM test are indicated in this section. Use the Cummins service publications[9] (Annex A6) for the preparation of other engine components. Take precautions to prevent rusting of iron components.

8.1.2 *Engine Block*—Disassemble the engine, including removal of the crankshaft, camshaft, piston cooling tubes, oil pump, and oil gallery plugs. Thoroughly clean the surfaces and oil passages (galleries). Use a brush to clean the oil passages. Removal of camshaft bearings is at the discretion of the laboratory.

8.1.3 *Cylinder Head*—Disassemble and clean the cylinder head. Use a brush as necessary to remove deposits.

8.1.4 *Rocker Cover and Oil Pan*—Clean the rocker cover and oil pan. Use a brush as necessary to remove deposits.

8.1.5 *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.

8.1.6 *Crosshead Cleaning and Measurement:*

8.1.6.1 *Handling and Orientation*—Avoid handling the crossheads with bare hands; use gloves or plastic covered tongs. Orient the crossheads in the engine with the elongated slot toward the exhaust valve.

8.1.6.2 Clean the crossheads with solvent. Use a nonmetallic soft bristle brush if necessary.

8.1.6.3 Spray the crossheads with air until dry.

8.1.6.4 Rinse the crossheads in pentane and dry with air.

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

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

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

(2) Measure the crosshead two times. Make the second measurement with the crossheads in an orientation that is 90° from the original orientation. If the difference between the two mass measurements is greater than 0.2 mg, demagnetize the crosshead and repeat the measurement process.

8.1.7 *Rod Bearing Cleaning and Measurement:*

8.1.7.1 Clean the rod bearings with solvent. Use a nonmetallic soft bristle brush if necessary. Avoid handling the rod bearings with bare hands. Use gloves or plastic covered tongs.

8.1.7.2 Spray the rod bearings with air until dry.

8.1.7.3 Rinse the rod bearings in pentane and dry with air.

8.1.7.4 Measure the mass of each bearing half to a tenth of a milligram (xxx.x mg).

8.1.8 *Ring Cleaning and Measurement:*

8.1.8.1 Clean and measure the rings in accordance with the Mack Test Ring Cleaning and Measuring procedure, available from the TMC.[8] Avoid handling the rings with bare hands. Use gloves or plastic covered tongs.

8.1.9 *Injector Adjusting Screw Cleaning and Measurement:*

8.1.9.1 Clean the injector adjusting screws with solvent. Use a soft bristle brush if necessary. Avoid handling the injector adjusting screws with bare hands. Use gloves or plastic covered tongs.

8.1.9.2 Spray the injector adjusting screws with air until dry.

8.1.9.3 Rinse the injector adjusting screws with pentane and dry with air.

8.1.9.4 Measure injector adjusting screw mass to a tenth of a milligram (xxx.x mg).

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

(1) Demagnetize each injector adjusting screw prior to measurement.

(2) Measure the adjusting screw two times. Make the second measurement with the injector adjusting screw in an orientation that is 90° from the original orientation. If the difference between the two mass measurements is greater than 0.2 mg, demagnetize the injector adjusting screw and repeat the measurement process.

8.2 *Engine Assembly:*

8.2.1 *General*—Except as noted in this section, use the procedures indicated in the Cummins service publications[9] (Annex A6). Assemble the engine with the components from the Engine Build Parts Kit[6] (Annex A3).

8.2.2 *Parts Reuse and Replacement*—Engine components may be reused or replaced at the discretion of the laboratory, except as noted in 8.2.7.

8.2.3 *Build-Up Oil*—Use Cummins Premium Blue[9] or test oil to lubricate parts for the engine build. If test oil is used, then the engine build is valid only for the respective test oil.

8.2.4 *Coolant Thermostat*—Lock the engine coolant thermostat open.

8.2.5 *Oil Thermostat*—Remove the oil thermostat and plug the oil passage. This will route all of the oil flow through the oil cooler (Fig. A4.2).

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[10] Available from Chevron Phillips Chemical Company LP, 10001 Six Pines Drive, Suite 4036B, The Woodlands, TX 77387-4910, fuels@cpchem.com.

[11] Available from the TMC website at http://www.astmtmc.org/ftp/docs/fuel/tmc-monitored%20test%20fuel%20specifications.pdf.

8.2.6 *Fuel Injectors*—The fuel injectors may be reused. Dedicate the injectors to a particular cylinder. Install the injectors in accordance with the torque wrench method as noted in the Cummins service publications (Annex A6).

8.2.7 *New Parts*—The parts listed below are contained in the Engine Build Parts Kit and are not reusable (except as noted in 10.3.3). Clean the parts prior to use. Replacement of any part listed below during a test invalidates the test.

8.2.7.1 Pistons (crown, skirt)
8.2.7.2 Piston Rings (top, second, oil)
8.2.7.3 Cylinder Liners
8.2.7.4 Rocker Lever Shafts
8.2.7.5 Rocker Levers (exhaust, intake, injector)
8.2.7.6 Rocker Lever Sockets (intake and exhaust)
8.2.7.7 Valves (intake, exhaust)
8.2.7.8 Valve Stem Guides
8.2.7.9 Valve Inserts
8.2.7.10 Piston Cooling Nozzles
8.2.7.11 Valve Crossheads
8.2.7.12 Connecting Rod Bearings
8.2.7.13 Adjusting Screws

8.3 *Operational Measurements:*

8.3.1 *Units and Formats*—See Annex A7.

8.3.2 *Instrumentation Calibration:*

8.3.2.1 *Fuel Consumption Rate Measurement Calibration*—Calibrate the fuel consumption rate measurement system before every reference test sequence and at least once every nine months. Temperature-compensate volumetric systems, and calibrate them against a mass flow device. The flowmeter located on the test stand shall indicate within 0.2 % of the calibration standard. Trace the calibration standard to national standards.

8.3.2.2 *Calibration of the Temperature Measurement Systems*—Calibrate the temperature measurement systems before every reference oil test sequence. Each temperature measurement system shall indicate within ±0.5 °C of the laboratory calibration standard. Trace the calibration standard to national standards.

8.3.2.3 *Calibration of the Pressure Measurement Systems*—Calibrate the pressure measurement systems before every reference oil test sequence. Trace the calibration standard to national standards.

8.3.3 *Temperatures:*

8.3.3.1 *Measurement Location*—The temperature measurement locations are specified in this section. 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 Data Acquisition and Control Automation II Task Force Report[8] 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 in the ¾ in. NPT hole at the top of the coolant out tube (Fig. A4.10).

8.3.3.3 *Coolant In Temperature*—Install the sensor on the right side of the coolant pump intake housing at the 1-in. NPT port (Fig. A4.11).

8.3.3.4 *Fuel In Temperature*—Install the sensor in the fuel pump inlet fitting (Fig. A4.5).

8.3.3.5 *Oil Gallery Temperature*—Install the sensor at the ¼-in. NPT hole on the left rear of the engine (Fig. A4.5 and Fig. A4.12).

8.3.3.6 *Intake Air Temperature*—Install the sensor (Fig. A4.6).

8.3.3.7 *Intake Manifold Temperature*—Install the sensor 30 mm from the outside edge of the manifold and 16 mm forward from the air inlet to the manifold. (Fig. A4.8, Fig. A4.9).

8.3.3.8 *Exhaust Temperature*—Install the sensor (Fig. A4.7).

8.3.3.9 *Additional*—Monitor any additional temperatures considered to be beneficial.

NOTE 2—Additional exhaust sensor locations are recommended, such as the exhaust ports and pre-turbine (front and rear). The detection of changes in exhaust temperature(s) is an important diagnostic. Measurement of the EGR cooler gas inlet and outlet temperatures and coolant inlet and outlet temperatures is recommended.

8.3.4 *Pressures:*

8.3.4.1 *Measurement Location and Equipment*—The pressure measurement locations are specified in this section. The measurement equipment is not specified. Follow the guidelines detailed in the Data Acquisition and Control Automation II Task Force Report[8] for the accuracy and resolution of the pressure measurement sensors and the complete measurement system.

8.3.4.2 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.

8.3.4.3 *Oil Gallery Pressure*—Measure the pressure at the left-rear of the engine, in the ⅜-in. NPT port behind ECM, in front of the oil gallery temperature measurement location (Fig. A4.5 and Fig. A4.12).

8.3.4.4 *Oil Filter Inlet Pressure*—Measure the pressure at the ⅞ in.-14 o-ring plug located on the oil filter assembly (Fig. A4.2).

8.3.4.5 *Oil Filter Outlet Pressure*—Measure the pressure at the ¼-in. NPT port located on the oil filter assembly (Fig. A4.2).

8.3.4.6 *Intake Manifold Pressure*—Measure the pressure at the ¼-in. NPT port located on the intake air elbow (Fig. A4.13).

8.3.4.7 *Crankcase Pressure*—Measure the pressure at the boss on the top-front, left-hand side of the rocker cover (Fig. A4.8).

8.3.4.8 *Intake Air Pressure*—Measure the pressure on the intake air tube (Fig. A4.6).

8.3.4.9 *Exhaust Pressure*—Measure the pressure on the exhaust tube (Fig. A4.7).

8.3.4.10 *Fuel Pressure*—Measure the pressure at the 9⁄16 in.-18 Compucheck adapter on fuel pump body (Fig. A4.5).

8.3.4.11 *Coolant Pressure*—Measure the pressure on top of the expansion tank (Fig. X1.3).

8.3.4.12 *Additional Pressures*—Monitor any additional pressures considered to be beneficial.

8.3.5 *Flow Rates:*

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8.3.5.1 *Flow Rate Location and Measurement Equipment*—The flow rate measurement locations are specified in this section. The equipment for the blowby rate and the fuel rate are not specified. Follow the guidelines detailed in the Data Acquisition and Control Automation II Task Force Report[8] for the accuracy and resolution of the flow rate measurement system.

8.3.5.2 *Blowby*—The device used to measure the blowby flow rate is not specified. See 6.2.11 for blowby measurement system configuration details.

8.3.5.3 *Fuel Flow*—The fuel consumption rate is determined by measuring the fuel flowing to the day tank (Fig. X1.2).

8.3.6 *Intake and Exhaust CO_2 Measurement:*

8.3.6.1 *Sampling Probes*—Instructions for obtaining general specifications and fabrication details for the intake and exhaust CO_2 probes are shown in Appendix X1. The intake and exhaust probes may also be obtained from the CPD.[6]

8.3.6.2 *Sampling Probe Locations*—Install the intake CO_2 probe 51 mm forward from the manifold pressure sensor on the same centerline (Fig. A4.14). The exhaust CO_2 probe location is shown in Fig. A4.7.

8.3.6.3 *Sampling Probe Insertion Depths*—Insert the intake CO_2 probe until it touches the bottom of the manifold, and then back the probe out 12 mm. A diagram of the insertion depth for the exhaust probe is shown in Fig. A4.15.

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

9.1 *General*—Calibrate the test stand by conducting a test with a blind reference oil.[8] Submit the results to the ASTM Test Monitoring Center (TMC) for determination of acceptance in accordance with the Lubricant Test Monitoring System (LTMS).[8]

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9.2 *New Test Stand*—A new test stand is defined as a test stand that has never been calibrated.

9.2.1 *New Test Stand Calibration*—New stand calibration is determined in accordance with the LTMS.[8]

9.3 *Stand Calibration Period*—The calibration period is 12 months. Up to 12 operationally valid, non-reference oil tests, including any non-interpretable tests, may be completed during each calibration period.

9.3.1 The TMC may schedule more frequent reference oil tests or extend the calibration period.

9.4 *Stand Modification and Calibration Status*—Stand calibration status can be invalidated by conducting any non standard test or modification of the test and control systems or both. A non standard test includes any test conducted under a modified procedure, nonprocedural hardware, controller set point modifications, or any combination thereof. Contact the TMC prior to any changes to determine the effect on the calibration status.

9.5 *Test Numbering System:*

9.5.1 *General*—The test number has three parts, *X-Y-Z*. *X* represents the test stand number, *Y* represents the engine serial number, and *Z* represents the stand run number. For example, test number 27-4B4607-2 indicates stand number 27, engine serial number 4B4607, and stand run number 2. Increment *Z* by one for each test start (reference oil and non-reference oil) with the exception stated in 9.5.2.

9.5.2 *Reference Oil Tests*—A reference oil test conducted subsequent to an unacceptable reference oil test shall include a letter suffix after *Z*. The letter suffix shall begin with *A* and increment alphabetically until an acceptable reference oil test is completed. For example, if two consecutive unacceptable reference oil tests were conducted and the first test number was 27-4B4607-10, the second test number would be 27-4B4607-10A. A third calibration attempt would have the test number 27-4B4607-10B. If the third test was acceptable, then 27-4B4607-10B would identify the reference oil test in the test report.

9.5.3 *Non-Reference Oil Tests*—Do not add a letter suffix to *Z* 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.[8]

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 11.7, 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 EOT date.

9.8 *Last Start Date*—In order for a non-reference oil test to be within a calibration period, crank the assembled engine (10.3.3) prior to the expiration of the calibration period (9.3).

9.9 *Donated Reference Oil Test Programs*—The 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.

9.10 *Adjustments to Reference Oil Calibration Periods:*

9.10.1 *Procedural Deviations*—On occasions when a laboratory becomes aware of a significant deviation from the test method, such as might arise during an inhouse 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.

9.10.2 *Parts and Fuel Shortages*—Under special circumstances, such as industry-wide 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.

9.10.3 *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 will incur no net loss (or gain) in calibration status.

9.10.4 *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 tests and 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.

10. Test Procedure

10.1 *Engine Installation and Stand Connections*—Install the test engine on the stand and connect the engine to the stand support equipment.

NOTE 3—A final check of valve and injector settings is recommended at this time.

10.2 *Coolant System Fill*—Install a new coolant filter, Cummins WF-2071. Fill the cooling system with premixed Fleetguard Compleat PG.[9] The coolant for non-reference oil tests may be reused provided the level of inhibitors is within specification as determined by DCA Level Test Kit, Cummins P/N CC2602.[9] Use new coolant for each reference oil test.

NOTE 4—The coolant system should be pressurized to specification and checked for leaks prior to adding the test oil.

10.3 *Oil Fill for Break-in:*

10.3.1 Install a new Cummins LF-3000 oil filter.[9]

10.3.2 Use the pressurized oil fill system (6.2.8) to charge the engine with 24.7 kg of test oil at the location shown in Fig. A4.2.

10.3.3 *Engine Build Committed*—After the test oil has been introduced into the engine, the engine build and the test number are valid only for the respective test. However, if the engine has not been cranked (whereby the test parts have not been subjected to wear or injected fuel, or both), then the new parts may be used again. Disassemble and clean the engine in accordance with 8.1.

TABLE 3 Warm-up Conditions

Parameter	Unit	Stage				
		A	B	C	D	E
Stage Length	min	5	5	5	5	5
Speed	r/min	700	1200	1600	1600	1600
Torque	N·m	135	270	540	1085	1470
Coolant Out Temperature	°C	75 max	75 max	75 max	75 max	75 max
Oil Gallery Temperature	°C	125 max	125 max	125 max	125 max	125 max
Intake Manifold Temperature	°C	70 max	70 max	70 max	70 max	70 max

10.4 *Fuel Samples*—Take a 120 mL fuel sample at the start of the test and at EOT.

10.5 *Engine Warm-up*—The engine warm-up conditions are shown in Table 3.

10.5.1 *Shutdown During Warm-up*—If a shutdown occurs during the warm-up, rerun the entire warm-up.

10.6 *Engine Break-in*—Perform a break-in on each new engine build prior to the start of the 200 h test procedure. The break-in conditions are shown in Table 4.

10.6.1 Start the engine, perform the warm-up (Table 3) and proceed directly to the break-in (Table 4).

10.6.1.1 *Shutdown during Break-in*—Stop the break-in timer at the initiation of a shutdown. When the laboratory is ready to resume the break-in, start the engine, perform the warm-up, and proceed to the break-in conditions. The break-in timer shall resume when the engine speed and torque are within specifications. If a shutdown occurs within the last 10 min of break-in, the break-in may be considered complete. Note such an occurrence in *Other Comments* section of Form 13 listed in Table A8.1.

10.6.2 At the completion of the break-in, perform a normal shutdown (Table 5) and shut off the engine.

10.6.3 Drain the oil from the engine and the external oil system.

10.6.4 Remove the LF-3000 oil filter.

10.6.5 Properly dispose of the drain oil and oil filter.

10.6.6 Once completed, the break-in is not repeated for the respective test.

NOTE 5—Use the break-in as an opportunity to confirm engine performance and to make repairs prior to the start of the 200 h test procedure.

10.7 *Shutdown and Maintenance*—The test may be shut down at the discretion of the laboratory to perform repairs. However, the intent of this test method is to conduct the 200 h test procedure without shutdowns.

10.7.1 *Normal Shutdown*—Proceed directly from the operating conditions to the shutdown schedule (Table 5).

10.7.2 *Emergency Shutdown*—An emergency shutdown occurs when the normal shutdown cannot be performed, such as an alarm condition. Note such an occurrence in the *Other Comments* section of Form 13 listed in Table A8.1.

10.7.3 *Maintenance*—Engine components or stand support equipment, or both, may be repaired or replaced at the discretion of the laboratory and in accordance with this test method.

TABLE 4 Break-in Conditions

Parameter	Unit	Specification
Stage Length	min	120
Speed	r/min	1600 ± 5 (target)
Torque (typical)[A]	N·m	1830
Fuel Flow	kg/h	64.4 ± 0.9 (target)
Coolant Out Temperature	°C	65.5
Fuel In Temperature	°C	40 ± 2
Oil Gallery Temperature	°C	115.0
Turbo Inlet Air Temperature	°C	record
Intake Manifold Temperature	°C	65.5 (target)
Oil Gallery Pressure	kPa	record
Oil Filter Delta Pressure	kPa	record
Intake Manifold Pressure	kPa abs.	≥ 320
Exhaust Pressure	kPa abs.	107 ± 1
Crankcase Pressure	kPa	record
Inlet Air Pressure	kPa abs.	record
Coolant System Pressure	kPa	99-107

[A] At standard atmospheric temperature and pressure.

TABLE 5 Normal Shutdown Conditions

Parameter	Unit	Stage		
		A	B	Idle
Stage Length	min	5	5	5
Speed	r/min	1200	700	700
Torque	N·m	270	135	< 40
Coolant Out Temperature	°C	75 max	75 max	75 max
Intake Manifold Temperature	°C	70 max	70 max	70 max
Oil Gallery Temperature	°C	125 max	125 max	125 max

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10.7.3.1 Removal of the crossheads prior to test completion shall invalidate the test.

10.7.3.2 Determine removal and replacement of the oil filter due to engine gallery pressure below 200 kPa solely at the discretion of the laboratory. Use the following guidelines for oil filter replacement:

(1) If the test is on a non-reference oil test and the test has not completed Stage C in Table 1, the test is considered non-interpretable (11.10).

(2) If the test is on a non-reference oil test and the test has completed Stage C in Table 1, the test can be continued with a new oil filter. Note an oil filter change in the *Other Comments* section of Form 13 listed in Table A8.1.

(3) Complete reference oil tests using the original oil filter in order to be considered operationally valid reference tests.

10.7.4 *Downtime*—The limit for total downtime and number of shutdowns is not specified. Record all shutdowns, pertinent actions, and total downtime during the 200 h test procedure on Form 13 listed in Table A8.1.

10.8 *200 h Test Procedure:*

10.8.1 Measure and record the mass of a new test oil filter, Cummins P/N 390383200 (Table A3.1), and install the oil filter on the engine.

10.8.2 *Oil Fill for Test*—Use the pressurized oil fill system (6.2.8) to charge the engine with 24.7 kg of test oil at the location shown in Fig. A4.2.

10.8.2.1 *New Oil Sample*—Take a 0.23 kg oil sample of the fresh oil from the original oil container.

10.8.3 Start the engine and perform the warm-up (Table 3).

10.8.4 *Operating Conditions*—After warm-up, proceed directly to the 200 h Test Sequence (Table 1). Contact Cummins Materials Engineering for Cummins engineering tool settings. Adjust the EGR valve using the Cummins engineering tool to attain the CO_2 level in Table 1. At the beginning of Stage A and C, retard the injection timing as necessary. At the beginning of Stage B and D, set the injection timing at 4.2 BTDC in the Cummins engineering tool.

10.8.4.1 *Stage Transition Times*—1 min (revolutions per minute only), 15 min (Intake Manifold Temperature).

10.8.5 *Injection Timing Change*—Injection timing may be adjusted at any time during Stage A or Stage C to ensure the oil soot level meets the soot targets shown in 10.8.6.1 and 10.8.6.2. Fix the injection timing at 4.2 during Stage B and D.

10.8.6 *Mass Percent Soot Validity:*

10.8.6.1 *Reference Oil Test*—Mass percent soot shall be (6.5 ± 0.5) % at 150 h.

10.8.6.2 *Non-Reference Oil Test*—Mass percent soot shall be 6.0 % minimum at 150 h.

10.8.7 *Test Timer*—The 200 h test timer starts when all controlled parameters in Stage A shown in Table 1 are within specification. If a shutdown occurs, stop the test timer immediately at the initiation of the shutdown. The test timer shall resume when the test has been returned to the appropriate stage and all controlled parameters are within specification.

10.8.7.1 The test timer continues incrementing test time throughout stage transitions.

10.8.8 *Operational Data Acquisition*—Record all operational parameters shown in Table 1, except blowby flowrate and intake CO_2, with automated data acquisition at a minimum frequency of once every 6 min. Record blowby flowrate a minimum of once every 8 h. Record intake and exhaust CO_2 once every 10 h, but not during a test stage transition. Recorded values shall have minimum resolution in accordance with Annex A7.

10.8.8.1 The operational data is reported on Form 5 listed in Table A8.1.

10.8.9 *Oil Sampling*—Take an oil sample at the end of each 25 h period before any new oil is added during the oil addition procedure. Remove the EOT oil sample within 30 min of the test completion. Do not shut down the engine for oil sampling and oil addition.

10.8.9.1 Remove a nominal 240 mL purge. Remove a nominal 120 mL oil sample. Return the purge to the engine oil system. Identify the oil sample container with the test number, oil code, date, and test hour.

10.8.10 *Oil Addition*—Establish the full mark after 1 h in Stage A conditions. After the oil sampling has been completed at the end of each 25 h period, check the oil mass. Drain a sufficient amount of oil to obtain an oil mass that is 1.4 kg below the full mark. If the oil mass is more than 1.4 kg below the full mark, do not perform a forced oil drain. Add 1.4 kg of new oil to the engine except at 200 h.

10.9 *End of Test (EOT):*

10.9.1 After completing the test procedure, perform a normal shutdown (Table 5), and shut down the engine. Release the coolant system pressure and drain the coolant. Disconnect the test stand support equipment (**Warning—**The coolant and oil may be hot. The installation of a valve to safely vent the coolant system pressure is recommended.)

10.9.2 Drain the oil from the engine and the external oil system. Begin the oil drain within 2 h after shutdown and allow a minimum duration of 30 min.

10.9.3 *Engine Disassembly*—Disassemble the engine and remove the following components for ratings and measurements:

10.9.3.1 *Rocker Cover and Oil Pan*—The rocker cover and oil pan may either remain on the engine or be removed from the engine. Maintain the rocker cover and oil pan in a horizontal position in the same orientation as installed on the engine for a minimum of 6 h after the EOT oil drain.

10.9.3.2 *Rocker Cover and Oil Pan Sludge Rating*—After 6 h in a horizontal plane, place the oil pan and rocker cover at a 60° angle from horizontal (lengthwise) with the front end and the inside surface down for a minimum of 8 h in a temperature-controlled environment. Maintain the temperature between (24 ± 3) °C.

11. Calculations, Ratings and Test Validity

11.1 *Crosshead Mass Loss*—Use the procedure shown in 8.1.6 to determine individual EOT crosshead mass.

11.1.1 Separate the crossheads into intake and exhaust groups.

11.1.2 Calculate the mass loss for each crosshead (pre-test - post test), and report the results. Calculate the average crosshead mass loss for the intake and exhaust groups.

11.1.3 Calculate the average mass loss, $\bar{x}$, and the standard deviation of the mass loss, *s*, for each group and report as *As Measured* in the *Intake/Exhaust Summary* section of Form 6 listed in Table A8.1.

11.1.4 Use Practice E178, two-sided test at a 95 % significance level, to determine if any crosshead mass loss values are outliers. Determine outliers for the intake and exhaust groups separately. Remove a maximum of one outlier per group Calculate the average mass loss, $\bar{x}$, and the standard deviation of the mass loss, *s*, for each group and report as *Outlier Screened* in the *Intake/Exhaust Summary* section of Form 6 listed in Table A8.1.

11.1.5 Calculate the average and the standard deviation of all mass loss values combined (intake and exhaust). Report the average, minimum, maximum and standard deviation as *As Measured* in the *Overall Summary* section of Form 6 listed in Table A8.1.

11.1.6 Calculate the average and the standard deviation of each group (intake and exhaust) using all mass loss values with outliers removed. Report the average, minimum, maximum and standard deviation as *Outlier Screened* in the *Overall Summary* section of Form 6 listed in Table A8.1.

11.1.7 Calculate the following and report as *Adjusted to 3.9 % Soot* in the *Overall Summary* section of Form 6 listed in Table A8.1:

$$\text{Crosshead Mass Loss Outlier Screened and Adjusted to 3.9\,\% Average Soot Mass} = \text{OSCHW} + 3(3.9 - \text{AVGSOOT}) \quad (1)$$

where:

OSCHW = Outlier Screened Crosshead Average Mass Loss value in the Overall Summary, and
AVGSOOT = mathematical average of the nine 25 h soot values (from 0 to 200) h, reported to one decimal.

11.1.7.1 Apply the following crosshead mass loss correction factors as necessary:

(1) For all tests that complete on or after June 28, 2007 and started on or before March 3, 2010, add a correction factor of +1.7 mg to the crosshead mass loss value calculated in 11.1.7.

(2) For all tests that started on or after March 4, 2010 and started on or before April 29, 2011, add a correction factor of +1.3 mg to the crosshead mass loss value calculated in 11.1.7.

(3) For all tests that start on or after April 30, 2011 on crosshead batches prior to batch "G" add a correction factor of +2.5 mg to the crosshead mass loss value calculated in 11.1.7.

(4) For all tests on batch "G" crossheads add a correction factor of +0.6 mg to the crosshead mass loss value calculated in 11.1.7.

(5) If after applying the appropriate correction factor from 11.1.7.1, the final crosshead mass loss value is less than 0, report the crosshead mass loss as 0 in 11.1.7.

11.2 *Injector Adjusting Screw Mass Loss*—Use the procedure shown in 8.1.9 to determine individual EOT adjusting screw mass.

11.2.1 Calculate the mass loss for each injector adjusting screw (pre-test – post test), and report the results in the main section on Form 12 listed in Table A8.1.

11.2.2 Calculate the average mass loss, $\bar{x}$, and the standard deviation of the mass loss, *s*, for the injector adjusting screws. Report the average mass loss as *Average As Measured* in the main section of Form 12 listed in Table A8.1.

11.2.3 Use Practice E178, two-sided test at a 95 % significance level, to determine if any injector adjusting screw mass loss values are outliers. Remove a maximum of one outlier. Calculate the average mass loss, $\bar{x}$, and the standard deviation of the mass loss, *s*, and report as *Outlier Screened* in the summary section of Form 12 listed in Table A8.1.

11.2.4 Calculate the following and report as *Average Adjusted to 3.9 % Soot* in the main section of Forms 4 and 12 listed in Table A8.1:

$$\text{SAIAS} = \exp\left(\ln(\text{OSIAS}) + 1.7(3.9 - \text{AVGSOOT})\right) \quad (2)$$

where:

SAIAS = Injector Adjusting Screw Outlier Screened and Adjusted to 3.9 % Average Soot Mass,
OSIAS = Outlier Screened Injector Adjusting Screw Average Mass Loss value in the Overall Summary, and
AVGSOOT = mathematical average of the nine 25 h soot values (from 0 to 200) h, reported to one decimal.

11.2.5 *Injector Adjusting Screw Correction Factor:*

11.2.5.1 For all tests that complete on or after June 28, 2007 on central parts distributor hardware kits 672 and below, add a correction factor of +19.1 mg to the injector adjusting screw

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mass loss average value adjusted to 3.9 % soot calculated in 11.2.4. Report this corrected value on Form 4 as the final result listed in Table A8.1.

11.2.5.2 For all tests that complete on hardware combinations consisting of Batch B injector push rods, Batch D injector adjusting screws, and Batch E crossheads (central parts distributor hardware kits 673 and above), take the natural log of the injector adjusting screw mass loss average value adjusted to 3.9 % soot calculated in 11.2.4 and reported on Form 12, add a correction factor of –0.200 to that value to get the transformed corrected IAS mass loss value and report on Form 4. Finally, back transform this value using the inverse natural log to get the final injector adjusting screw mass loss value in milligrams. Report this value on Form 4 as the final result listed in Table A8.1.

11.2.5.3 For all tests that complete on hardware combinations consisting of Batch C injector push rods, Batch D injector adjusting screws and Batch F crossheads (central parts distributor hardware kits numbered 938 or higher) and all subsequent batches of hardware for tests completing before March 22nd 2022, take the natural log of the injector adjusting screw mass loss average value adjusted to 3.9 % soot calculated in 11.2.4 and reported on Form 12, apply a correction factor of +0.410 to that value to get the transformed corrected IAS mass loss value and report on Form 4. Finally, back transform this value using the inverse natural log to get the final injector adjusting screw mass loss value in milligrams. Report this value on Form 4 as the final result listed in Table A8.1.

11.2.5.4 For all tests that complete after March 22nd 2022 on hardware combinations consisting of Batch C injector push rods, Batch E injector adjusting screws and Batch G crossheads and all subsequent batches of hardware, take the natural log of the injector adjusting screw mass loss average value adjusted to 3.9 % soot calculated in 11.2.4 and reported on Form 12, apply a correction factor of +0.250 to that value to get the transformed corrected IAS mass loss value and report on Form 4. Finally, back transform this value using the inverse natural log to get the final injector adjusting screw mass loss value in milligrams. Report this value on Form 4 as the final result listed in Table A8.1.

11.3 *Ring Mass Loss*—Use the procedure shown in 8.1.8 to determine individual EOT ring mass.

11.3.1 Calculate the mass loss for the top, second, and oil rings (pre-test – post-test). Report the mass loss for the top, second, and oil rings in the upper portion of the main section of Form 9 listed in Table A8.1.

11.3.2 Calculate the average mass loss, $\bar{x}$, and the standard deviation of the mass loss, s, for the top, second and oil ring groups. Report the maximum, minimum, average mass loss, and the standard deviation of the mass loss for the top ring group in the *As Measured Results* section of Form 9 listed in Table A8.1.

11.3.3 Use Practice E178, two-sided test at a 95 % significance level, to determine if any top ring mass loss values are outliers. Remove a maximum of one outlier. Calculate the average mass loss, $\bar{x}$, and the standard deviation of the mass loss, s, and report the maximum, minimum, average mass loss, and the standard deviation of the mass loss for the top ring group as *Outlier Screened* in the summary section of Form 9 listed in Table A8.1.

11.4 *Sludge Ratings:*

11.4.1 Rate the rocker arm cover sludge and the oil pan sludge in accordance with ASTM Deposit Rating Manual 20[4] at the locations specified in Figs. A9.1 and A9.2.

11.4.2 Average the rocker arm cover sludge and oil pan sludge ratings. Report as *Average Sludge Rating* on Form 8 listed in Table A8.1.

11.5 *Oil Filter Plugging*—Oil filter plugging (ΔP_{FP}) is indicated by the increase of the oil filter differential pressure (ΔP) during the test. The general equation for oil filter plugging is as follows:

$$\Delta P_{FP} = \Delta P_{(MAX)} - \Delta P_{INIT} \tag{3}$$

$$\Delta P = \text{Oil Filter Outlet Pressure} - \text{Oil Filter Inlet Pressure}$$

where:

$\Delta P_{(MAX)}$ = maximum ΔP recorded from (0 to 150) h, and
ΔP_{INIT} = first ΔP reading of the test with target and range parameters within specification.

11.5.1 Plot oil filter ΔP versus test hour on Form 7 listed in Table A8.1.

11.5.2 Report $\Delta P(FP)$ as oil filter ΔP in Form 4 listed in Table A8.1.

11.5.3 *Oil Filter Plugging Correction Factor*—For all tests that start on or after October 1, 2014, apply a correction factor of +4 kPa to the values reported in 11.5.2 and report that value on Form 4 listed in Table A8.1.

11.6 *Oil Analyses*—Analyze the oil samples for viscosity at 100 °C, wear metals (iron, copper, lead, chromium, and aluminum), TAN, TBN, and percent soot mass (TGA) in accordance with the schedule and methods shown in Annex A11.

11.7 *Oil Consumption*—Sum the mass of the oil consumed for the test.

11.8 *Fuel Analyses*—Report the analyses provided by the fuel supplier on Form 11 listed in Table A8.1. Report the analyses of the final batch if more than one fuel batch was used.

11.8.1 *Additional Analyses*—Perform the following analyses on the 120 mL new and EOT fuel samples:

11.8.1.1 API Gravity, Test Method D287 or D4052.

11.8.1.2 Total Sulfur, mass percent, Test Method D5453 (D2622 or D4294 can be substituted).

11.9 *Assessment of Operational Validity*—Determine operational validity in accordance with Annex A11.

11.10 *Assessment of Test Interpretability*—A test is non-interpretable when the total oil consumption exceeds 15 kg. A non-reference test is non-interpretable when the 150 h soot mass is less than 6.0 % (10.8.6).

12. Test Report

12.1 *Report Forms*—For reference oil tests the standardized report form set and data dictionary for reporting test results and

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