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SURFACE VEHICLE RECOMMENDED PRACTICE

An American National Standard

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(R) TEST PROCEDURE FOR THE MEASUREMENT OF GASEOUS EXHAUST EMISSIONS FROM SMALL UTILITY ENGINES

Foreword—This Document has also changed to comply with the new SAE Technical Standards Board format.

1. Scope—This SAE Recommended Practice specifies a uniform procedure for the evaluation of gaseous exhaust emissions from small utility engines typically less than 20 kW. Details of engine test setup and exhaust gas analysis techniques are specified with the intent of providing a uniform and reproducible method of measurement.

The intent has been to allow as much flexibility as possible in the physical construction of the experimental apparatus. Therefore, only those portions of the apparatus whose operation is critical to the accurate measurement of emissions levels are prescribed in detail.

An engine test procedure including a test sequence is outlined such that it would cover the various applications in which small engines are used. The intent is to provide an understanding of the levels of exhaust emissions and does not imply that in a given application, an engine would operate in all the modes outlined in the test procedure.

This document is intended as a guide toward standard practice and is subject to change to keep pace with experience and technical advances.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein. The latest issue of SAE Publications shall apply.

2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J177—Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust
SAE J215—Continuous Hydrocarbon Analysis of Diesel Emissions
SAE J244—Measurement of Intake Air or Exhaust Gas Flow of Diesel Engines
SAE J254—Instrumentation and Techniques for Exhaust Gas Emissions Measurement
SAE J313—Diesel Fuels
SAE Paper 650507—Air Fuel Ratios From Exhaust Gas Analysis, R.S. Spindt

2.1.2 FEDERAL REGULATIONS—Available from The Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

Code of Federal Regulations, 40 CFR 86.310-79
Code of Federal Regulations, 86.113-87
Code of Federal Regulations, 86.144-78

3. Definitions

3.1 "100% LOAD" is the maximum load which can be applied at a given engine condition.

3.2 "IDLE SPEED" is the manufacturer's recommended idle speed. If there is no recommended idle speed, the idle speed will be the lowest stable engine speed without a load.

3.3 "INTERMEDIATE SPEED" is 85% of rated speed.

3.4 "RATED POWER" is specified by the manufacturer at a rated speed.

3.5 "RATED SPEED" means the speed specified by the manufacturer at the rated power for the engine. If the rated speed is not specified, the rated speed will be at the point at which the engines peak power occurs.

4. Engine Test Setup—The engine under test, or the test cell, should be instrumented so that the following variables, in addition to exhaust emission levels, can be measured:

a. Inlet air temperature
b. Inlet air humidity (Test cell)
c. Barometric pressure (Test cell)
d. Fuel mass flow rate
e. Engine speed
f. Engine brake torque output

Throughout the course of a test, exhaust composition will be measured through use of an analytical train and instrumentation system to be described subsequently.

Suggested engine setup and exhaust gas analysis systems are illustrated in Figures 1, 2, and 3, respectively. Engine test cell ambient conditions shall remain within the following tolerances:

a. Ambient Air Temperature—20 to 30 °C

4.1 Air and Fuel Flow Measurement—Emissions measurements are made on a molar basis and results are given in terms of concentration. General practice at present is to quote emissions in mass terms. Conversion of concentrations into mass should be based on the fuel flow technique. For all engines it is recommended to use the Fuel Flow Method as described in 7.2.2.1. The following paragraphs give recommended procedures for measuring air and fuel flow.

4.1.1 FUEL FLOW MEASUREMENT—Fuel flow rate measurement instrumentation must have a combined accuracy of ±2% of the reading.

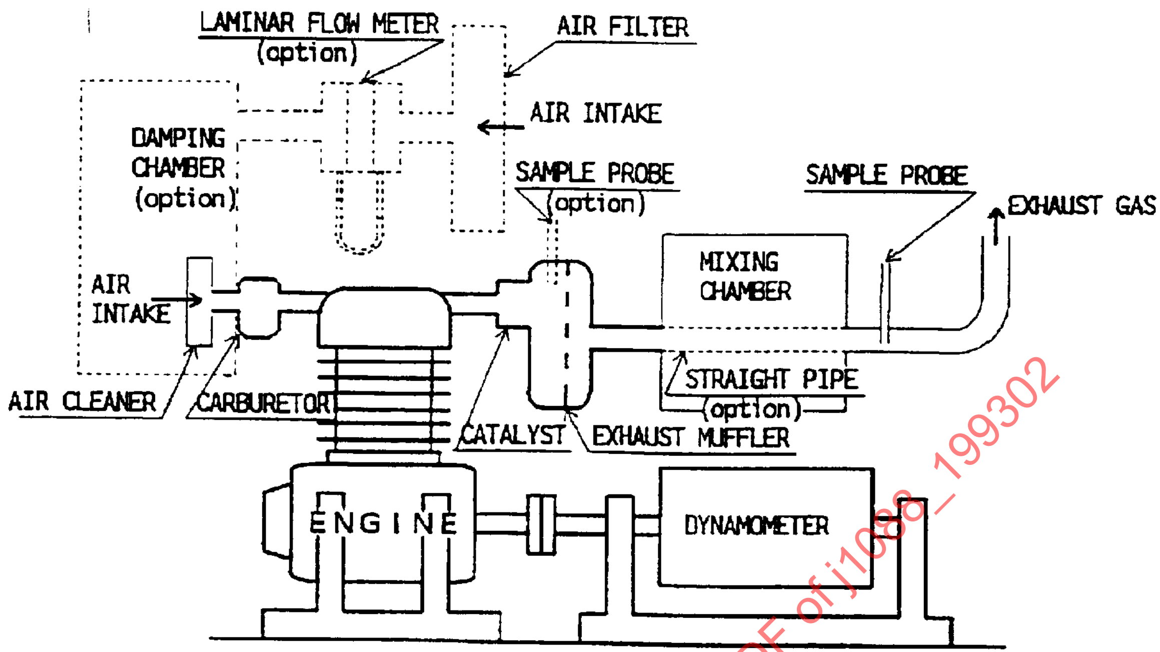

FIGURE 1—ENGINE SETUP FOR EMISSIONS TEST

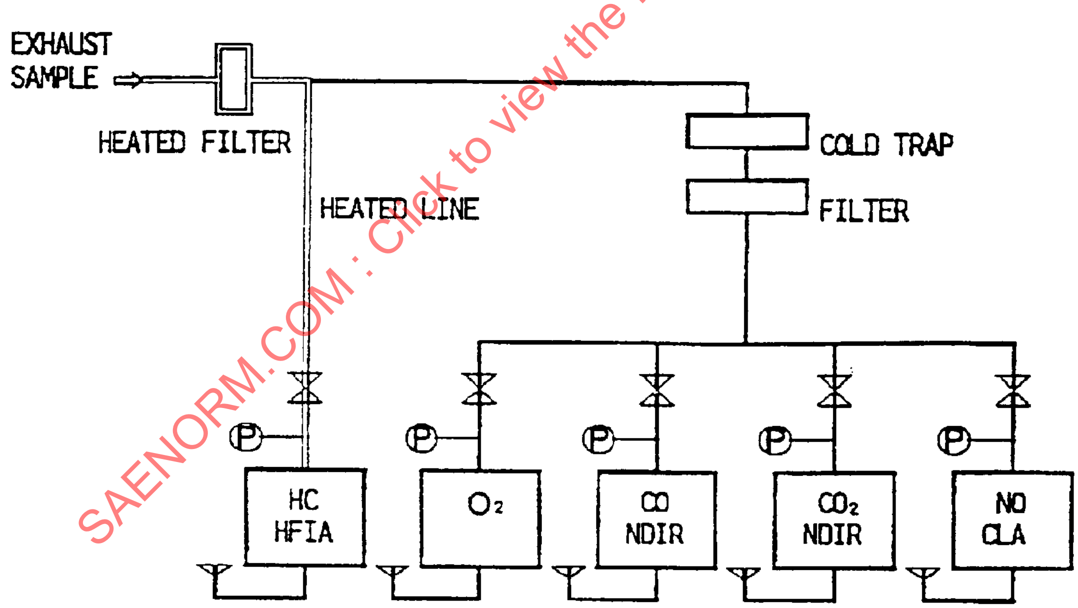

FIGURE 2—EXHAUST GAS ANALYTICAL SYSTEM WITH CLA

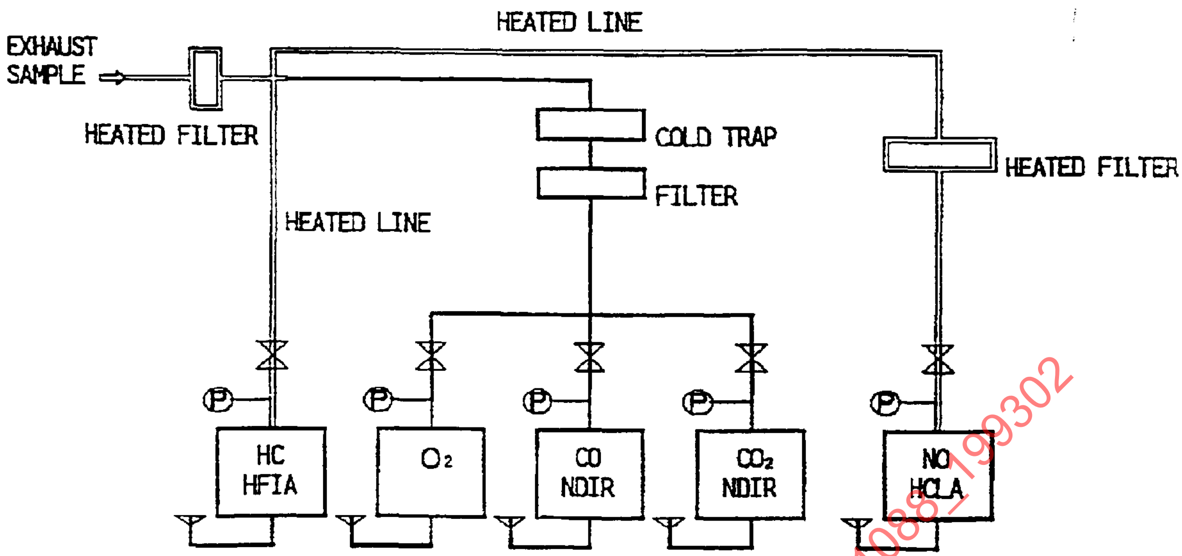

FIGURE 3—EXHAUST GAS ANALYTICAL SYSTEM WITH HCLA

4.1.2 INLET AIR FLOW MEASUREMENT (OPTIONAL)—Figure 1 shows in schematic form an optional inlet airflow measurement system. The measurement system shown consists of a laminar flow meter used in conjunction with a pressure wave damping chamber. The damping chamber may consist of any vessel having an internal volume not less than 100 times the displacement per cylinder under test. The damping chamber should be installed between the airflow metering element and the engine air inlet, thus serving to isolate the meter from the engine. One of a number of alternate airflow measurement systems may be substituted for the preferred system described previously. Such systems should adhere to the practices specified by SAE J244.

If the airflow element reduces the engine airflow because of excessive pressure drop, greater than 100 Pa, an auxiliary blower can be used to compensate for the effect of the air meter. If a blower is used, engine inlet pressure should be measured and controlled to ±50 Pa of barometer readings.

4.2 Exhaust Gas Sampling System—The exhaust gas sampling system consists of the exhaust system normally supplied with the engine, an exhaust sampling probe, and an exhaust mixing chamber. Figure 1 shows a typical sampling system. Figure 4 shows the sample probe and typical hole spacings.

4.2.1 EXHAUST SAMPLE PROBE—The sample probe shall be a straight, closed end, stainless steel, multi-hole probe. The Inside Diameter (ID) shall not be greater than the ID of the sample line. The wall thickness of the probe shall not be greater than 1 mm. The fitting that attaches the probe to exhaust conduit shall be as small as practical in order to minimize heat loss from the probe.

There shall be a minimum of three holes in the probe. The spacing of the radial planes for each hole in the probe must be such that they cover approximately equal cross-sectional areas of the exhaust conduit. The angular spacing of the holes must be approximately equal. The angular spacing of any two holes in one plane may not be 180 degrees ± 20 degrees (i.e., section C-C of Figure 4). The holes should be sized such that each has approximately the same flow. If only three holes are used, they may not all be in the same radial plane.

The probe shall extend radially across the exhaust conduit. The probe must pass through the approximate center and must extend across at least 80% of the diameter of the conduit.

The exhaust sample probe information given previously was taken from the Code of Federal Regulations, 40 CFR 86.310-79.

4.2.2 EXHAUST MIXING CHAMBER—The mixing chamber is located in the exhaust system between the muffler and the sample probe. Its purpose is to ensure complete mixing of the engine exhaust before sample extraction so that a truly representative average exhaust sample is obtained. The internal volume of the mixing chamber must be not less than 10 times the cylinder displacement of the engine under test and should be of roughly equal dimensions in height, width, and depth.

To minimize dropout of heavy hydrocarbon fractions in the exhaust mixing chamber during part throttle, light load operation, the chamber size should be kept as small as practical, consistent with the 10 times cylinder displacement minimum size limitation. Restricting the size of the chamber will keep internal turbulence as high as possible, thus promoting thorough mixing of the exhaust gas. The chamber should be coupled as close as possible to the engine.

The exhaust line leaving the chamber should extend a sufficient length beyond the sample probe location to eliminate possible sampling errors due to strong exhaust pulsations pulling air back into the exhaust system. The exhaust line should be of sufficient size to hold exhaust back pressure to a minimum. The temperature of the inner surface of the mixing chamber must be maintained above the dew point of the exhaust gases. A temperature range of 175 to 400 °C is recommended. It is suggested that surface thermocouples or other suitable monitoring devices be installed in the mixing chamber to ensure operation at the proper temperatures.

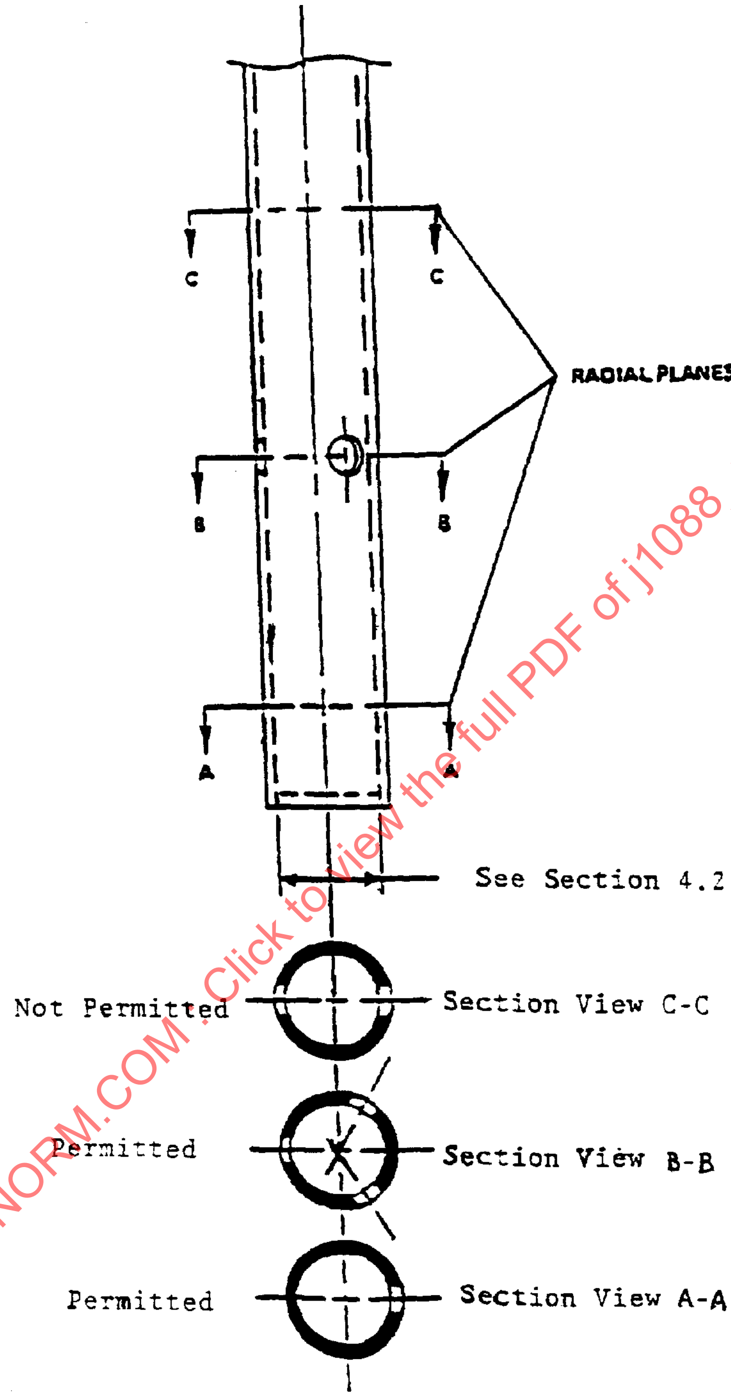

FIGURE 4—EXHAUST SAMPLE PROBE

4.2.3 ALTERNATE EXHAUST GAS SAMPLING SYSTEMS—One of a number of exhaust gas sampling methods may be substituted for the preferred method described in 4.2.2 and seen in Figure 1 if it can be shown the alternate method provides a homogeneous representative exhaust gas sample and avoids dilution by aspiration of ambient air. If a mixing chamber is not used, the exhaust sampling probe shall be located in the exhaust conduit downstream of the exhaust valve or exhaust port of a single-cylinder engine or downstream of the final junction of the exhaust manifold of a multi-cylinder engine. If the exhaust sample probe is located in the muffler, it should be positioned in the high-pressure side of the muffler. If the engine is equipped with an exhaust catalytic convertor, the exhaust sample probe shall be located downstream from the catalytic element but not so close to the exhaust outlet as to ingest air from the atmosphere due to pressure pulsations in the exhaust.

5. Exhaust Gas Analysis

5.1 Analytical Methods—The following instruments will be used to measure exhaust concentrations of the species listed as follows: (The instrument should be capable of an accuracy of 2% of point value or 1% of full scale, whichever is less.)

5.1.1 UNBURNED HYDROCARBONS—Heated flame ionization detector (FID).

Operation of the analyzer should conform to the procedure specified in SAE J215. If SAE J215 is not applicable to a specific instrument, the manufacturer's recommendations should be followed. An oven temperature in the range of 175 to 200 °C is recommended for both 2-stroke cycle and 4-stroke cycle engines.

5.1.2 CARBON MONOXIDE—Nondispersive infrared analyzer (NDIR).

Operation of the infrared analyzer should conform to the practice specified in SAE J254 and/or SAE J177.

5.1.3 CARBON DIOXIDE—Nondispersive infrared analyzer (NDIR).

Operation of this analyzer should follow recommendations given in SAE J254 and/or SAE J177.

5.1.4 OXIDES OF NITROGEN—Chemiluminescent Analyzer (CLA). Heated Chemiluminescent Analyzer (HCLA).

Recommendations for operation of the chemiluminescent analyzer are given in SAE J177 practices.

If the operating recommendations given in the SAE J177 practices are not applicable to the particular make of chemiluminescent analyzer being used, follow instrument manufacturer's recommendations.

5.1.5 OXYGEN—POLAROGRAPH OR PARAMAGNETIC—Oxygen measurement may provide an indication of air leaks in the system. Operation should conform to SAE J254.

5.2 Exhaust Sample Preparation and Analysis—A suggested analytical system which provides for continuous measurement of emissions levels is illustrated in Figure 2 or 3. The drawings are not intended to represent a complete system. Rather, they are intended to show the essential elements of such a system.

Exhaust gases from the sample probe are split into two or three streams depending upon sampling requirements. One sample line leads to the heated FID. This line should be heated to the same temperature as the detector oven. 175 to 200 °C is recommended. This line also should have a heated particulate filter to remove contaminants.

A second sample line leads to the NDIR and CLA analyzers. The sample passes through a cold trap (0 to 7 °C sample gas temperature), which serves to remove the water, and then through a filter. The filtered, dry exhaust gases are pumped by diaphragm pumps to the analytical instruments. It is recommended that the sample line leading to an HCLA be kept at a temperature of more than 60 °C and be provided with a heated particulate filter. The inlet of each analyzer is provided with a metering valve to permit adjustment of flow rate through that instrument. Sample flow rates are indicated by flow meters placed in the exhaust of each analyzer. In addition, gauges are provided for measurement of pressure at the sample inlet port of each analyzer.

5.3 Instrument Checkout and Calibration—Periodic calibration, adjustment, and minimum warm-up time should be performed as specified by the instrument manufacturer and as dictated by experience with each individual analyzer. Instrument test and adjustment procedures shall follow those specified within SAE J177, SAE J215, and/or SAE J254.

6. Engine Test Procedure

6.1 Engine Preparation—Test the engine on the dynamometer, under mode point one of appropriate test cycle, measuring fuel consumption and power before and after the emission measuring equipment is installed. The emission sampling equipment shall not significantly affect the operational characteristics of the engine. (Typically, the results should agree within 5%.) Particular attention must be exercised during engine mounting on the dynamometer as the fuel flow and emissions may be greatly influenced by the mounting configuration such as friction, vibration, and air flow.

6.1.1 FUEL SPECIFICATIONS—Although any fuel can be used with this test procedure, it is recommended that:

a. For gasoline engines it is desirable to use an EPA certified test fuel such as Indolene Clear as described in the Code of Federal Regulations, 86.113-87 or other alternate certification test fuels as appropriate.
b. For diesel engines, use the D2 fuel specification stated in SAE J313 except that the percent sulfur should be limited to 0.05% by dry weight.
c. For other fuels, either its molecular weight per carbon (MF) or H/C atomic ratio (y) and O/C atomic ratio (z) must be recorded on the data sheet.

For some nonoxygenated fuels Table 1:

TABLE 1—NONOXYGENATED FUELS

Fuel	y	z	MF
gasoline	1.85	0	13.88
diesel	1.80	0	13.83
methane	4.00	0	16.04
propane	2.67	0	14.69

6.1.2 LUBRICATING OIL—During all engine tests, the engine should employ a lubricating oil consistent with the engine manufacturer's specifications for that particular engine. For 2-stroke-cycle engines, the fuel-oil mixture ratio should conform to the engine manufacturer's recommendations.

6.1.3 ENGINE RUN-IN PRIOR TO BEGINNING ENGINE EXHAUST EMISSION TESTS—The engine should be run-in in accordance with the manufacturer's instructions.

6.1.4 ENGINE START-UP—Prior to starting the emissions tests, the engine should be allowed to warm up in accordance with the manufacturer's instructions. Before proceeding with the tests, the carburetor and engine adjustments should be set to the manufacturer's recommendations.

6.2 Exhaust Emission Test Sequence Measurement Procedure—The test sequence is a series of steady-state operating modes. Standard sequences are presented in Figure 5. Additional operating modes may be added for more comprehensive emission mapping. It should be understood that once coupled to the end product, the engine may seldom operate in some of the modes shown in Figure 5. Modes are to be performed in the numerical order specified for the appropriate test cycle. At the manufacturer's option, testing may be performed with locked throttle in a fixed position or using the engine governor. During the idle, no load mode, the engine may or may not be coupled to the dynamometer. In either case, test records should indicate which method was selected.

Once engine speed and load are set for a mode, the engine shall be run for a sufficient period of time to achieve thermal stability. The goal is to stabilize all engine parameters affecting emissions production and performance output before recorded measurement begins. Temperatures of combustion chamber components are good indicators of engine stability. After thermal stability is achieved, emissions measurements are initiated.

All data used to calculate emissions shall be averaged for a period of at least 2 min. Longer averaging times may be required to ascertain the true time averaged emissions if data variability over time is significant. Discrete data sampling must occur sufficiently fast to ensure accurate measurement of time averages. Data sample intervals should be less than 1/2 the response time of the fastest instrument. At the completion of the measurement, the engine is set to the next mode.

7. Data Reduction and Presentation of Results

7.1 Engine Performance—The following engine operating and performance parameters should be presented for each test in the units indicated in Table 2.

TABLE 2—ENGINE OPERATING AND PERFORMANCE PARAMETERS

Parameter	Units SI
Air flow rate (Optional)	g/h
Fuel flow rate	g/h
Engine speed	r/min
Engine torque output	N·m
Power output	kW
Air inlet temperature	°C
Air humidity	mg/kg
Coolant temperature (liquid cooled)	°C
Exhaust mixing chamber surface temperature (Optional)	°C
Exhaust sample line temperature	°C
Total accumulated hours of engine operation	h
Barometric pressure	kPa

Mode	1	2	3	4	5	6	7	8	9	10	11
Speed	--rated speed--					--intermediate speed--					idle
Mode points A cycle						1	2	3	4	5	6
Load % A cycle						100	75	50	25	10	0
Mode points B cycle	1	2	3	4	5						6
Load % B cycle	100	75	50	25	10						0
Mode points C cycle	1										2
Load % C cycle	100										0

NOTE—It is recommended that the mode points be run (as numbered) in order of decreasing temperature (highest to lowest power mode).

Choosing an Appropriate Test Cycle—If the primary end use of an engine model is known then the test cycle may be chosen based on the examples given in the cycle description. If the primary end use of an engine model is uncertain, then an appropriate test cycle should be chosen based upon the engine specifications. Both compression ignition and spark ignition engines may be tested in any of the three cycles, whichever is most appropriate.

A Cycle—Non-handheld intermediate speed applications such as, but not limited to: walk behind rotary or reel lawn mowers, front or rear engine riding lawn mowers, rotary tillers, edger trimmers, waste disposers, lawn sweepers, sprayers, snow removal equipment.

B Cycle—Non-handheld rated speed applications such as, but not limited to: portable generators, pumps, welders, air compressors. Rated speed applications may also include lawn and garden equipment which operates at engine rated speed.

C Cycle—Handheld rated speed applications such as, but not limited to: edge trimmers, string trimmers, blowers, vacuums, chain saws.

FIGURE 5—STANDARD SEQUENCES

7.2 Exhaust Species Concentrations

7.2.1 INITIAL MOLAR CONCENTRATIONS—In all HC designation the C is expressed in C1.

Concentrations of each of the exhaust species will be measured in the following units:

Unburned Hydrocarbons (HC)	Molar ppm C1 (in wet exhaust)
CO_2	Mole percent (in dry exhaust)
CO	Mole percent (in dry exhaust)
NO	Molar ppm (in dry or wet exhaust measured by chemiluminescent analyzer)
O_2	Mole percent (in dry exhaust)

7.2.2 CONVERSION TO MASS EMISSION RATES—Conversion to mass terms should be wet species concentration data, but care must be taken that all data are reported on the same basis. Since engine emissions are discharged to the atmosphere in the wet state, it would seem reasonable to report emissions concentrations on a wet basis.

For this reason, the conversion equations given as follows are written for use with wet concentration data. A suggested method for converting dry concentration data into wet terms is given in Appendix A.

Two methods may be used to calculate mass rate of discharge. One method makes use of both air and fuel flow data. The other method is based upon fuel flow alone.

7.2.2.1 *Fuel Flow Method*—These equations are based on the same assumptions used for the combined air/fuel method. A correction for the mass effect of humidity on NOx species concentration is included in the equations. The error introduced by neglecting the effect of humidity on other exhaust species concentrations in insignificant when the overall accuracy of measurement is considered and, therefore, is considered as part of the experimental error.

$$HC, g/h = MHCexh/MF * Fuel,g/h /(TC) * HC,ppmC\ w * 1/10000 \quad \text{(Eq. 1)}$$

$$CO, g/h = MCO/MF * Fuel, g/h /(TC) * CO, \%\ w \quad \text{(Eq. 2)}$$

$$NOx, g/h = MNOx/MF * Fuel, g/h /(TC) * NOx,ppm\ w * KH * 1/10000 \quad \text{(Eq. 3)}$$

where:

1. (TC) = CO, % wet + CO_2, % wet + HC, % wet
2. If fuel is in lb/h, divide by 0.002205
3. MHCexh = MF, molecular weight of fuel = 12.011 + 1.008 * y + 15.999 * z

NOTE—This assumes that the exhaust hydrocarbons are identical to unburned fuel.)

4. MF = molecular weight of fuel
5. MCO = molecular weight of CO = 28.01
6. MNOx = molecular weight of NO_2 (NOx) = 46.01
7. y = H/C hydrogen/carbon atomic ratio of the fuel
   z = O/C oxygen/carbon atomic ratio of the fuel
8. KH = Federal factor for correcting the effect of humidity on NO_2 formation

$$= \frac{1}{[1 - 0.0329 * (H - 10.71)]} \text{ (Gasoline)} \quad \text{(Eq. 4)}$$

$$= \frac{1}{[1 - 0.0182 * (H - 10.71)]} \text{ (Diesel)} \quad \text{(Eq. 5)}$$

where:

H = grams of moisture per kilogram of dry air

The humidity correction factor given previously was taken from the code of Federal Regulations, 40 CFR 86.144-78. This correction factor has not been verified for small engines. Moreover, the NOx emissions for small engines are low and the KH factor approaches one in a laboratory test environment. The KH factor for two-stroke cycle engines should be set to "1" regardless of humidity.

7.2.2.2 Air and Fuel Flow Method—The following equations may be used to calculate mass emissions when both air and fuel flows are measured.

$$HC, g/h = (airflow, g/h + fuel\ flow, g/h) \times \frac{MHCexh}{ME} \times HC, ppmC\ w \times 1/1000000 \quad \text{(Eq. 6)}$$

$$CO, g/h = (airflow, g/h + fuel\ flow, g/h) \times \frac{MCO}{ME} \times CO, \%\ wet \times 1/100 \quad \text{(Eq. 7)}$$

$$NOx, g/h = (airflow, g/h + fuel\ flow, g/h) \times \frac{MNO_2}{ME} \times NOx, ppm\ w \times KH \times 1/1000000 \quad \text{(Eq. 8)}$$

where:

1. If airflow or fuel flow are in lb/h rather than g/h, divide by 0.002205
2. ME, molecular weight of exhaust is calculated using the equation specified as follows
3. Refer to 7.2.2.1 for molecular weight information and humidity correction factor KH

The following equation may be used to determine the molecular weight of the exhaust:

$$\begin{aligned} mol\ wt\ exh = {} & \frac{13.88 \times HC\ ppm\ C1_W}{10^6} + \frac{28.01 \times CO\%_W}{10^2} \quad \text{(Eq. 9)} \\ & + \frac{44.01\ CO_2\%_W}{10^2} + \frac{46.01 \times NOx\ ppm_W}{10^6} + \frac{32.00 \times O_2\%_W}{10^2} \\ & + \frac{2.016 \times H_2\%_W}{10^2} + 18.01 \times (1-K) + \{28.01 \times [100 - \frac{HCppm\ C1_W}{10^4} \\ & - CO\%_W - CO_2\%_W - \frac{NOxppm_W}{10^4} - O_2\%_W - (H_2\%_W) - 100 \times (1-K)]\}/10^2 \end{aligned}$$

where:

$$K = \frac{1}{1 + 0.005 \times (CO\%_d + CO_2\%_d) \times y - 0.01 \times H_2\%_d} \quad \text{(Eq. 10)}$$

$$H_2\%_d = \frac{0.5 \times y \times CO\%_d \times (CO\%_d + CO_2\%_d)}{CO\%_d + 3 \times CO_2\%_d} \quad \text{(Eq. 11)}$$

$y = H/C$ atomic ratio of test fuel

For two-stroke cycle engines, we assume no residual free H_2 and modify K by deleting the H_2 term.

In some cases it may not be practical to measure fuel flow. The fuel/air ratio, however, can be determined from the exhaust products of nonoxygenated fuels using the Spindt method (SAE Paper 650507). With this information available, the term (airflow) x (1 + F/A) may be substituted for the (airflow + fuel flow) term in the preceding equations. This substitution is valid for 4-stroke cycle engines only. It does not apply to 2-stroke cycle engines.