

Table 2G-5. Wind Tunnel Axial Flow Verification

Wind Tunnel Facility: \_\_\_\_\_  
 Date: \_\_\_\_\_  
 Wind Tunnel Temperature: \_\_\_\_\_  
 Barometric Pressure: \_\_\_\_\_  
 Probe Type/I.D. Used To Conduct Check: \_\_\_\_\_  
 Test Point Locations: \_\_\_\_\_  
 Lowest Test Velocity in m/sec (ft/sec): \_\_\_\_\_  
 Highest Test Velocity in m/sec (ft/sec): \_\_\_\_\_

Port		@ Lowest Test Velocity		@ Highest Test Velocity	
		Yaw Angle * (degrees)	Pitch Angle * (degrees)	Yaw Angle * (degrees)	Pitch Angle * (degrees)
Calibration Location Test Points **	1				
	2				
	3				
	..				
Calibration Pitot Tube Location					

\* When following the procedures in section 10.1.2.1, both the yaw and pitch angles are obtained from the same port. When following the procedures in section 10.1.2.2, the yaw angle is obtained using the port for the tested probe, and the pitch angle is obtained using the port for verification of axial flow.

\*\* Yaw and pitch angle measurements must be taken at all points that define the calibration location (as per the requirements in section 10.1.1)

Specification: At each velocity setting, each measured yaw and pitch angle shall be within  $\pm 3^\circ$  of  $0^\circ$  in accordance with the requirements in section 10.1.2.

**Table 2G-6. Yaw Angle Calibration**

Probe Type: \_\_\_\_\_ Tester(s): \_\_\_\_\_  
 Probe ID: \_\_\_\_\_ Affiliation: \_\_\_\_\_  
 Test Location: \_\_\_\_\_ Date: \_\_\_\_\_

Nominal Velocity Setting in m/sec (ft/sec)	Repetition 1		Repetition 2	
	$\theta_{null}$ (degrees)	$R_{SLO}$ (degrees)*	$\theta_{null}$ (degrees)	$R_{SLO}$ (degrees)*
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
Average of all recorded $R_{SLO}$ values: _____				

\* Include magnitude and algebraic sign in accordance with section 10.5.6.

**Table 2G-7. Determining the Magnitude of Reference Scribe Line Offset**

Probe/Angle-Measuring Device	Magnitude of $R_{SLO}$
Type S probe with inclinometer	$\theta_{null}$
Type S probe with protractor wheel and pointer	$90^\circ - \theta_{null}$
3-D probe with inclinometer	$90^\circ - \theta_{null}$
3-D probe with protractor wheel and pointer	$\theta_{null}$

Table 2G-8. Probe Calibration for Method 2G

Wind Tunnel Facility: \_\_\_\_\_  
 Wind Tunnel Location: \_\_\_\_\_  
 Probe Type: \_\_\_\_\_  
 Probe ID: \_\_\_\_\_  
 Probe Calibration Date: \_\_\_\_\_  
 Test Point Location: \_\_\_\_\_  
 Ambient Temperature (°F): \_\_\_\_\_  
 Barometric Pressure (P<sub>bar</sub>): \_\_\_\_\_

Repetition	Low Velocity Setting (ft/sec)	Calibration Pitot		Tested Probe		Calculated C <sub>p</sub> or F <sub>2</sub>
		ΔP <sub>std</sub> (in. H <sub>2</sub> O)	Temp. (°F)	ΔP or P <sub>1</sub> -P <sub>2</sub> (in. H <sub>2</sub> O)	Yaw Angle (°)	
1						
2						
3						
Average (C <sub>p(avg-low)</sub> ) =						

Repetition	High Velocity Setting (ft/sec)	Calibration Pitot		Tested Probe		Calculated C <sub>p</sub> or F <sub>2</sub>
		ΔP <sub>std</sub> (in. H <sub>2</sub> O)	Temp. (°F)	ΔP or P <sub>1</sub> -P <sub>2</sub> (in. H <sub>2</sub> O)	Yaw Angle (°)	
1						
2						
3						
Average (C <sub>p(avg-high)</sub> ) =						

$$\% \text{ Difference} = \frac{C_{p(avg-low)} - C_{p(avg-high)}}{C_{p(avg-low)}} \times 100\% = \underline{\hspace{2cm}} \%$$

- Note:** (1) The percent difference between the low and high velocity setting C<sub>p</sub> values shall be within ±3 percent.  
 (2) If calibrating a 3-D probe for this method, the pitch angle setting must be 0°.

METHOD 2H—DETERMINATION OF STACK GAS VELOCITY TAKING INTO ACCOUNT VELOCITY DECAY NEAR THE STACK WALL

1.0 Scope and Application

1.1 This method is applicable in conjunction with Methods 2, 2F, and 2G (40 CFR Part 60, Appendix A) to account for velocity decay near the wall in circular stacks and ducts.

1.2 This method is not applicable for testing stacks and ducts less than 3.3 ft (1.0 m) in diameter.

1.3 Data Quality Objectives. Adherence to the requirements of this method will enhance the quality of the data obtained from air pollutant sampling methods.

2.0 Summary of Method

2.1 A wall effects adjustment factor is determined. It is used to adjust the average stack gas velocity obtained under Method 2, 2F, or 2G of this appendix to take into account velocity decay near the stack or duct wall.

2.2 The method contains two possible procedures: a calculational approach which derives an adjustment factor from velocity measurements and a default procedure which assigns a generic adjustment factor based on the construction of the stack or duct.

2.2.1 The calculational procedure derives a wall effects adjustment factor from velocity measurements taken using Method 2, 2F, or 2G at 16 (or more) traverse points specified under Method 1 of this appendix and a total of eight (or more) wall effects traverse points specified under this method. The calculational procedure based on velocity measurements is not applicable for horizontal circular ducts where build-up of particulate matter or other material in the bottom of the duct is present.

2.2.2 A default wall effects adjustment factor of 0.9900 for brick and mortar stacks and 0.9950 for all other types of stacks and ducts may be used without taking wall effects measurements in a stack or duct.

2.3 When the calculational procedure is conducted as part of a relative accuracy test audit (RATA) or other multiple-run test procedure, the wall effects adjustment factor derived from a single traverse (i.e., single RATA run) may be applied to all runs of the same RATA without repeating the wall effects measurements. Alternatively, wall effects adjustment factors may be derived for several traverses and an average wall effects adjustment factor applied to all runs of the same RATA.

3.0 Definitions.

3.1 *Complete wall effects traverse* means a traverse in which measurements are taken at  $d_{em}$  (see section 3.3) and at 1-in. intervals in each of the four Method 1 equal-area sectors closest to the wall, beginning not far-

ther than 4 in. (10.2 cm) from the wall and extending either (1) across the entire width of the Method 1 equal-area sector or (2) for stacks or ducts where this width exceeds 12 in. (30.5 cm) (i.e., stacks or ducts greater than or equal to 15.6 ft [4.8 m] in diameter), to a distance of not less than 12 in. (30.5 cm) from the wall. Note: Because this method specifies that measurements must be taken at whole number multiples of 1 in. from a stack or duct wall, for clarity numerical quantities in this method are expressed in English units followed by metric units in parentheses. To enhance readability, hyphenated terms such as "1-in. intervals" or "1-in. incremented," are expressed in English units only.

3.2  $d_{wall}$ . Depending on context,  $d_{wall}$  means either (1) the distance from the wall of the last 1-in. incremented wall effects traverse point or (2) the traverse point located at that distance (see Figure 2H-2).

3.3  $d_{cent}$ . Depending on context,  $d_{cent}$  means either (1) the distance from the wall of the centroid of the area between  $d_{wall}$  and the interior edge of the Method 1 equal-area sector closest to the wall or (2) the traverse point located at that distance (see Figure 2H-2).

3.4 "May," "Must," "Shall," "Should," and the imperative form of verbs.

3.4.1 "May" is used to indicate that a provision of this method is optional.

3.4.2 "Must," "Shall," and the imperative form of verbs (such as "record" or "enter") are used to indicate that a provision of this method is mandatory.

3.4.3 "Should" is used to indicate that a provision of this method is not mandatory but is highly recommended as good practice.

3.5 *Method 1* refers to 40 CFR part 60, appendix A, "Method 1—Sample and velocity traverses for stationary sources."

3.6 *Method 1 exterior equal-area sector and Method 1 equal-area sector closest to the wall* mean any one of the four equal-area sectors that are closest to the wall for a circular stack or duct laid out in accordance with section 2.3.1 of Method 1 (see Figure 2H-1).

3.7 *Method 1 interior equal-area sector* means any of the equal-area sectors other than the Method 1 exterior equal-area sectors (as defined in section 3.6) for a circular stack or duct laid out in accordance with section 2.3.1 of Method 1 (see Figure 2H-1).

3.8 *Method 1 traverse point and Method 1 equal-area traverse point* mean a traverse point located at the centroid of an equal-area sector of a circular stack laid out in accordance with section 2.3.1 of Method 1.

3.9 *Method 2* refers to 40 CFR part 60, appendix A, "Method 2—Determination of stack gas velocity and volumetric flow rate (Type S pitot tube)."

3.10 *Method 2F* refers to 40 CFR part 60, appendix A, "Method 2F—Determination of stack gas velocity and volumetric flow rate with three-dimensional probes."

3.11 *Method 2G* refers to 40 CFR part 60, appendix A, "Method 2G—Determination of stack gas velocity and volumetric flow rate with two-dimensional probes."

3.12 *1-in. incremented wall effects traverse point* means any of the wall effects traverse points that are located at 1-in. intervals, i.e., traverse points  $d_1$  through  $d_{max}$  (see Figure 2H-2).

3.13 *Partial wall effects traverse* means a traverse in which measurements are taken at fewer than the number of traverse points required for a "complete wall effects traverse" (as defined in section 3.1), but are taken at a minimum of two traverse points in each Method 1 equal-area sector closest to the wall, as specified in section 8.2.2.

3.14 *Relative accuracy test audit (RATA)* is a field test procedure performed in a stack or duct in which a series of concurrent measurements of the same stack gas stream is taken by a reference method and an installed monitoring system. A RATA usually consists of series of 9 to 12 sets of such concurrent measurements, each of which is referred to as a RATA run. In a volumetric flow RATA, each reference method run consists of a complete traverse of the stack or duct.

3.15 *Wall effects-unadjusted average velocity* means the average stack gas velocity, not accounting for velocity decay near the wall, as determined in accordance with Method 2, 2F, or 2G for a Method 1 traverse consisting of 16 or more points.

3.16 *Wall effects-adjusted average velocity* means the average stack gas velocity, taking into account velocity decay near the wall, as calculated from measurements at 16 or more Method 1 traverse points and at the additional wall effects traverse points specified in this method.

3.17 *Wall effects traverse point* means a traverse point located in accordance with sections 8.2.2 or 8.2.3 of this method.

#### 4.0 Interferences [Reserved]

#### 5.0 Safety

5.1 This method may involve hazardous materials, operations, and equipment. This method does not purport to address all of the health and safety considerations associated with its use. It is the responsibility of the user of this method to establish appropriate health and safety practices and to determine the applicability of occupational health and safety regulatory requirements prior to performing this method.

#### 6.0 Equipment and Supplies

6.1 The provisions pertaining to equipment and supplies in the method that is used to take the traverse point measurements (i.e.,

Method 2, 2F, or 2G) are applicable under this method.

#### 7.0 Reagents and Standards [Reserved]

#### 8.0 Sample Collection and Analysis

8.1 *Default Wall Effects Adjustment Factors.* A default wall effects adjustment factor of 0.9900 for brick and mortar stacks and 0.9950 for all other types of stacks and ducts may be used without conducting the following procedures.

8.2 *Traverse Point Locations.* Determine the location of the Method 1 traverse points in accordance with section 8.2.1 and the location of the traverse points for either a partial wall effects traverse in accordance with section 8.2.2 or a complete wall effects traverse in accordance with section 8.2.3.

8.2.1 *Method 1 equal-area traverse point locations.* Determine the location of the Method 1 equal-area traverse points for a traverse consisting of 16 or more points using Table 1-2 (Location of Traverse Points in Circular Stacks) of Method 1.

8.2.2 *Partial wall effects traverse.* For a partial wall effects traverse, measurements must be taken at a minimum of the following two wall effects traverse point locations in all four Method 1 equal-area sectors closest to the wall: (1) 1 in. (2.5 cm) from the wall (except as provided in section 8.2.2.1) and (2)  $d_{rem}$ , as determined using Equation 2H-1 or 2H-2 (see section 8.2.2.2).

8.2.2.1 If the probe cannot be positioned at 1 in. (2.5 cm) from the wall (e.g., because of insufficient room to withdraw the probe shaft) or if velocity pressure cannot be detected at 1 in. (2.5 cm) from the wall (for any reason other than build-up of particulate matter in the bottom of a duct), take measurements at the 1-in. incremented wall effects traverse point closest to the wall where the probe can be positioned and velocity pressure can be detected.

8.2.2.2 Calculate the distance of  $d_{rem}$  from the wall to within  $\pm 1/4$  in. (6.4 mm) using Equation 2H-1 or Equation 2H-2 (for a 16-point traverse).

$$d_{last} \leq d_b \quad \text{Eq. 2H-3}$$

Where:

$r$  = the stack or duct radius determined from direct measurement of the stack or duct diameter in accordance with section 8.6 of Method 2F or Method 2G, in. (cm);

$p$  = the number of Method 1 equal-area traverse points on a diameter,  $p \geq 8$  (e.g., for a 16-point traverse,  $p = 8$ );  $d_{last}$  and  $d_{rem}$  are defined in sections 3.2 and 3.3 respectively, in. (cm).

For a 16-point Method 1 traverse, Equation 2H-1 becomes:

$$d_{rem} = r - \sqrt{\frac{7}{8}r^2 - rd_{last}} + \frac{1}{2}d_{last}^2 \quad \text{Eq. 2H-2}$$

8.2.2.3 Measurements may be taken at any number of additional wall effects traverse points, with the following provisions.

(a)  $d_{last}$  must not be closer to the center of the stack or duct than the distance of the interior edge (boundary),  $d_b$ , of the Method 1 equal-area sector closest to the wall (see Figure 2H-2 or 2H-3). That is,

Where:

$$d_b = r \left( 1 - \sqrt{1 - \frac{2}{p}} \right) \quad \text{Eq. 2H-4}$$

Table 2H-1 shows  $d_b$  as a function of the stack or duct radius,  $r$ , for traverses ranging from 16 to 48 points (i.e., for values of  $p$  ranging from 8 to 24).

(b) Each point must be located at a distance that is a whole number (e.g., 1, 2, 3) multiple of 1 in. (2.5 cm).

(c) Points do not have to be located at consecutive 1-in. intervals. That is, one or more 1-in. incremented points may be skipped. For example, it would be acceptable for points to be located at 1 in. (2.5 cm), 3 in. (7.6 cm), 5 in. (12.7 cm),  $d_{last}$ , and  $d_{rem}$ ; or at 1 in. (2.5 cm), 2 in. (5.1 cm), 4 in. (10.2 cm), 7 in. (17.8 cm),  $d_{last}$ , and  $d_{rem}$ . Follow the instructions in section 8.7.1.2 of this method for recording results for wall effects traverse points that are skipped. It should be noted that the full extent of velocity decay may not be accounted for if measurements are not taken at all 1-in. incremented points close to the wall.

8.2.3 Complete wall effects traverse. For a complete wall effects traverse, measurements must be taken at the following points in all four Method 1 equal-area sectors closest to the wall.

(a) The 1-in. incremented wall effects traverse point closest to the wall where the probe can be positioned and velocity can be detected, but no farther than 4 in. (10.2 cm) from the wall.

(b) Every subsequent 1-in. incremented wall effects traverse point out to the interior edge of the Method 1 equal-area sector or to 12 in. (30.5 cm) from the wall, whichever comes first. Note: In stacks or ducts with diameters greater than 15.6 ft (4.8 m) the interior edge of the Method 1 equal-area sector is farther from the wall than 12 in. (30.5 cm).

(c)  $d_{rem}$ , as determined using Equation 2H-1 or 2H-2 (as applicable). Note: For a complete traverse of a stack or duct with a diameter less than 16.5 ft (5.0 m), the distance between  $d_{rem}$  and  $d_{last}$  is less than or equal to ½ in. (12.7 mm). As discussed in section 8.2.4.2, when the distance between  $d_{rem}$  and

$d_{last}$  is less than or equal to ½ in. (12.7 mm), the velocity measured at  $d_{last}$  may be used for  $d_{rem}$ . Thus, it is not necessary to calculate the distance of  $d_{rem}$  or to take measurements at  $d_{rem}$  when conducting a complete traverse of a stack or duct with a diameter less than 16.5 ft (5.0 m).

8.2.4 Special considerations. The following special considerations apply when the distance between traverse points is less than or equal to ½ in. (12.7 mm).

8.2.4.1 A wall effects traverse point and the Method 1 traverse point. If the distance between a wall effects traverse point and the Method 1 traverse point is less than or equal to ½ in. (12.7 mm), taking measurements at both points is allowed but not required or recommended; if measurements are taken at only one point, take the measurements at the point that is farther from the wall and use the velocity obtained at that point as the value for both points (see sections 8.2.3 and 9.2 for related requirements).

8.2.4.2  $d_{rem}$  and  $d_{last}$ . If the distance between  $d_{rem}$  and  $d_{last}$  is less than or equal to ½ in. (12.7 mm), taking measurements at  $d_{rem}$  is allowed but not required or recommended; if measurements are not taken at  $d_{rem}$ , the measured velocity value at  $d_{last}$  must be used as the value for both  $d_{last}$  and  $d_{rem}$ .

8.3 Traverse Point Sampling Order and Probe Selection. Determine the sampling order of the Method 1 and wall effects traverse points and select the appropriate probe for the measurements, taking into account the following considerations.

8.3.1 Traverse points on any radius may be sampled in either direction (i.e., from the wall toward the center of the stack or duct, or vice versa).

8.3.2 To reduce the likelihood of velocity variations during the time of the traverse and the attendant potential impact on the wall effects-adjusted and unadjusted average velocities, the following provisions of this method shall be met.

8.3.2.1 Each complete set of Method 1 and wall effects traverse points accessed from the same port shall be sampled without interruption. Unless traverses are performed simultaneously in all ports using separate probes at each port, this provision disallows first sampling all Method 1 points at all ports and then sampling all the wall effects points.

8.3.2.2 The entire integrated Method 1 and wall effects traverse across all test ports shall be as short as practicable, consistent with the measurement system response time

(see section 8.4.1.1) and sampling (see section 8.4.1.2) provisions of this method.

8.3.3 It is recommended but not required that in each Method 1 equal-area sector closest to the wall, the Method 1 equal-area traverse point should be sampled in sequence between the adjacent wall effects traverse points. For example, for the traverse point configuration shown in Figure 2H-2, it is recommended that the Method 1 equal-area traverse point be sampled between  $d_{\text{int}}$  and  $d_{\text{ext}}$ . In this example, if the traverse is conducted from the wall toward the center of the stack or duct, it is recommended that measurements be taken at points in the following order:  $d_1$ ,  $d_2$ ,  $d_{\text{int}}$ , the Method 1 traverse point,  $d_{\text{ext}}$ , and then at the traverse points in the three Method 1 interior equal-area sectors.

8.3.4 The same type of probe must be used to take measurements at all Method 1 and wall effects traverse points. However, different copies of the same type of probe may be used at different ports (e.g., Type S probe 1 at port A, Type S probe 2 at port B) or at different traverse points accessed from a particular port (e.g., Type S probe 1 for Method 1 interior traverse points accessed from port A, Type S probe 2 for wall effects traverse points and the Method 1 exterior traverse point accessed from port A). The identification number of the probe used to obtain measurements at each traverse point must be recorded.

8.4 Measurements at Method 1 and Wall Effects Traverse Points. Conduct measurements at Method 1 and wall effects traverse points in accordance with Method 2, 2F, or 2G and in accordance with the provisions of the following subsections (some of which are included in Methods 2F and 2G but not in Method 2), which are particularly important for wall effects testing.

8.4.1 Probe residence time at wall effects traverse points. Due to the steep temperature and pressure gradients that can occur close to the wall, it is very important for the probe residence time (i.e., the total time spent at a traverse point) to be long enough to ensure collection of representative temperature and pressure measurements. The provisions of Methods 2F and 2G in the following subsections shall be observed.

8.4.1.1 System response time. Determine the response time of each probe measurement system by inserting and positioning the "cold" probe (at ambient temperature and pressure) at any Method 1 traverse point. Read and record the probe differential pressure, temperature, and elapsed time at 15-second intervals until stable readings for both pressure and temperature are achieved. The response time is the longer of these two elapsed times. Record the response time.

8.4.1.2 Sampling. At the start of testing in each port (i.e., after a probe has been inserted into the stack gas stream), allow at

least the response time to elapse before beginning to take measurements at the first traverse point accessed from that port. Provided that the probe is not removed from the stack gas stream, measurements may be taken at subsequent traverse points accessed from the same test port without waiting again for the response time to elapse.

8.4.2 Temperature measurement for wall effects traverse points. Either (1) take temperature measurements at each wall effects traverse point in accordance with the applicable provisions of Method 2, 2F, or 2G; or (2) use the temperature measurement at the Method 1 traverse point closest to the wall as the temperature measurement for all the wall effects traverse points in the corresponding equal-area sector.

8.4.3 Non-detectable velocity pressure at wall effects traverse points. If the probe cannot be positioned at a wall effects traverse point or if no velocity pressure can be detected at a wall effects point, measurements shall be taken at the first subsequent wall effects traverse point farther from the wall where velocity can be detected. Follow the instructions in section 8.7.1.2 of this method for recording results for wall effects traverse points where velocity pressure cannot be detected. It should be noted that the full extent of velocity decay may not be accounted for if measurements are not taken at the 1-in. incremented wall effects traverse points closest to the wall.

8.5 Data Recording. For each wall effects and Method 1 traverse point where measurements are taken, record all pressure, temperature, and attendant measurements prescribed in section 3 of Method 2 or section 8.0 of Method 2F or 2G, as applicable.

8.6 Point Velocity Calculation. For each wall effects and Method 1 traverse point, calculate the point velocity value ( $v_p$ ) in accordance with sections 12.1 and 12.2 of Method 2F for tests using Method 2F and in accordance with sections 12.1 and 12.2 of Method 2G for tests using Method 2 and Method 2G. (Note that the term ( $v_p$ ) in this method corresponds to the term ( $v_{act}$ ) in Methods 2F and 2G.) When the equations in the indicated sections of Method 2G are used in deriving point velocity values for Method 2 tests, set the value of the yaw angles appearing in the equations to 0°.

8.7 Tabulating Calculated Point Velocity Values for Wall Effects Traverse Points. Enter the following values in a hardcopy or electronic form similar to Form 2H-1 (for 16-point Method 1 traverses) or Form 2H-2 (for Method 1 traverses consisting of more than 16 points). A separate form must be completed for each of the four Method 1 equal-area sectors that are closest to the wall.

- (a) Port ID (e.g., A, B, C, or D)
- (b) Probe type
- (c) Probe ID

(d) Stack or duct diameter in ft (m) (determined in accordance with section 8.6 of Method 2F or Method 2G)

(e) Stack or duct radius in in. (cm)

(f) Distance from the wall of wall effects traverse points at 1-in. intervals, in ascending order starting with 1 in. (2.5 cm) (column A of Form 2H-1 or 2H-2)

(g) Point velocity values ( $v_i$ ) for 1-in. incremented traverse points (see section 8.7.1), including  $d_{last}$  (see section 8.7.2)

(h) Point velocity value ( $v_{drem}$ ) at  $d_{rem}$  (see section 8.7.3).

8.7.1 Point velocity values at wall effects traverse points other than  $d_{last}$ . For every 1-in. incremented wall effects traverse point other than  $d_{last}$ , enter in column B of Form 2H-1 or 2H-2 either the velocity measured at the point (see section 8.7.1.1) or the velocity measured at the first subsequent traverse point farther from the wall (see section 8.7.1.2). A velocity value must be entered in column B of Form 2H-1 or 2H-2 for every 1-in. incremented traverse point from  $d_i$  (representing the wall effects traverse point 1 in. [2.5 cm] from the wall) to  $d_{last}$ .

8.7.1.1 For wall effects traverse points where the probe can be positioned and velocity pressure can be detected, enter the value obtained in accordance with section 8.6.

8.7.1.2 For wall effects traverse points that were skipped [see section 8.2.2.3(c)] and for points where the probe cannot be positioned or where no velocity pressure can be detected, enter the value obtained at the first subsequent traverse point farther from the wall where velocity pressure was detected and measured and follow the entered value with a "flag," such as the notation "NM," to indicate that "no measurements" were actually taken at this point.

8.7.2 Point velocity value at  $d_{last}$ . For  $d_{last}$ , enter in column B of Form 2H-1 or 2H-2 the measured value obtained in accordance with section 8.6.

8.7.3 Point velocity value ( $v_{drem}$ ) at  $d_{rem}$ . Enter the point velocity value obtained at  $d_{rem}$  in column G of row 4a in Form 2H-1 or 2H-2. If the distance between  $d_{rem}$  and  $d_{last}$  is less than or equal to  $\frac{1}{2}$  in. (12.7 mm), the measured velocity value at  $d_{last}$  may be used as the value at  $d_{rem}$  (see section 8.2.4.2).

#### 9.0 Quality Control.

9.1 Particulate Matter Build-up in Horizontal Ducts. Wall effects testing of horizontal circular ducts should be conducted only if build-up of particulate matter or other material in the bottom of the duct is not present.

9.2 Verifying Traverse Point Distances. In taking measurements at wall effects traverse points, it is very important for the probe impact pressure port to be positioned as close as practicable to the traverse point locations in the gas stream. For this reason, before beginning wall effects testing, it is

important to calculate and record the traverse point positions that will be marked on each probe for each port, taking into account the distance that each port nipple (or probe mounting flange for automated probes) extends out of the stack and any extension of the port nipple (or mounting flange) into the gas stream. To ensure that traverse point positions are properly identified, the following procedures should be performed on each probe used.

9.2.1 Manual probes. Mark the probe insertion distance of the wall effects and Method 1 traverse points on the probe sheath so that when a mark is aligned with the outside face of the stack port, the probe impact port is located at the calculated distance of the traverse point from the stack inside wall. The use of different colored marks is recommended for designating the wall effects and Method 1 traverse points. Before the first use of each probe, check to ensure that the distance of each mark from the center of the probe impact pressure port agrees with the previously calculated traverse point positions to within  $\pm\frac{1}{4}$  in. (6.4 mm).

9.2.2 Automated probe systems. For automated probe systems that mechanically position the probe head at prescribed traverse point positions, activate the system with the probe assemblies removed from the test ports and sequentially extend the probes to the programmed location of each wall effects traverse point and the Method 1 traverse points. Measure the distance between the center of the probe impact pressure port and the inside of the probe assembly mounting flange for each traverse point. The measured distances must agree with the previously calculated traverse point positions to within  $\pm\frac{1}{4}$  in. (6.4 mm).

9.3 Probe Installation. Properly sealing the port area is particularly important in taking measurements at wall effects traverse points. For testing involving manual probes, the area between the probe sheath and the port should be sealed with a tightly fitting flexible seal made of an appropriate material such as heavy cloth so that leakage is minimized. For automated probe systems, the probe assembly mounting flange area should be checked to verify that there is no leakage.

9.4 Velocity Stability. This method should be performed only when the average gas velocity in the stack or duct is relatively constant over the duration of the test. If the average gas velocity changes significantly during the course of a wall effects test, the test results should be discarded.

#### 10.0 Calibration

10.1 The calibration coefficient(s) or curves obtained under Method 2, 2F, or 2G and used to perform the Method 1 traverse are applicable under this method.



## 11.0 Analytical Procedure

11.1 Sample collection and analysis are concurrent for this method (see section 8).

## 12.0 Data Analysis and Calculations

12.1 The following calculations shall be performed to obtain a wall effects adjustment factor (*WAF*) from (1) the wall effects-unadjusted average velocity (*Tavg*), (2) the replacement velocity ( $\hat{v}_{ej}$ ) for each of the four Method 1 sectors closest to the wall, and (3) the average stack gas velocity that accounts for velocity decay near the wall ( $\hat{v}_{avg}$ ).

12.2 Nomenclature. The following terms are listed in the order in which they appear in Equations 2H-5 through 2H-21.

$v_{avg}$  = the average stack gas velocity, unadjusted for wall effects, actual ft/sec (m/sec);

$v_i$  = stack gas point velocity value at Method 1 interior equal-area sectors, actual ft/sec (m/sec);

$v_{ej}$  = stack gas point velocity value, unadjusted for wall effects, at Method 1 exterior equal-area sectors, actual ft/sec (m/sec);

$i$  = index of Method 1 interior equal-area traverse points;

$j$  = index of Method 1 exterior equal-area traverse points;

$n$  = total number of traverse points in the Method 1 traverse;

$vdec_d$  = the wall effects decay velocity for a sub-sector located between the traverse points at distances  $d-1$  (in metric units,  $d-2.5$ ) and  $d$  from the wall, actual ft/sec (m/sec);

$v_d$  = the measured stack gas velocity at distance  $d$  from the wall, actual ft/sec (m/sec); Note:  $v_0 = 0$ ;

$d$  = the distance of a 1-in. incremented wall effects traverse point from the wall, for traverse points  $d_j$  through  $d_{last}$ , in. (cm);

$A_d$  = the cross-sectional area of a sub-sector located between the traverse points at distances  $d-1$  (in metric units,  $d-2.5$ ) and  $d$  from the wall, in.<sup>2</sup> (cm<sup>2</sup>) (e.g., sub-sector  $A_2$  shown in Figures 2H-3 and 2H-4);

$r$  = the stack or duct radius, in. (cm);

$Q_d$  = the stack gas volumetric flow rate for a sub-sector located between the traverse points at distances  $d-1$  (in metric units,  $d-2.5$ ) and  $d$  from the wall, actual ft-in.<sup>2</sup>/sec (m-cm<sup>2</sup>/sec);

$Q_{d_{last} \rightarrow d_{first}}$  = the total stack gas volumetric flow rate for all sub-sectors located between the wall and  $d_{last}$ , actual ft-in.<sup>2</sup>/sec (m-cm<sup>2</sup>/sec);

$d_{last}$  = the distance from the wall of the last 1-in. incremented wall effects traverse point, in. (cm);

$A_{d_{first}}$  = the cross-sectional area of the sub-sector located between  $d_{last}$  and the interior edge of the Method 1 equal-area sec-

tor closest to the wall, in.<sup>2</sup> (cm<sup>2</sup>) (see Figure 2H-4);

$p$  = the number of Method 1 traverse points per diameter,  $p \geq 8$  (e.g., for a 16-point traverse,  $p = 8$ );

$d_{rem}$  = the distance from the wall of the centroid of the area between  $d_{last}$  and the interior edge of the Method 1 equal-area sector closest to the wall, in. (cm);

$Q_{d_{rem}}$  = the total stack gas volumetric flow rate for the sub-sector located between  $d_{last}$  and the interior edge of the Method 1 equal-area sector closest to the wall, actual ft-in.<sup>2</sup>/sec (m-cm<sup>2</sup>/sec);

$v_{d_{rem}}$  = the measured stack gas velocity at distance  $d_{rem}$  from the wall, actual ft/sec (m/sec);

$Q_r$  = the total stack gas volumetric flow rate for the Method 1 equal-area sector closest to the wall, actual ft-in.<sup>2</sup>/sec (m-cm<sup>2</sup>/sec);

$\hat{v}_{ej}$  = the replacement stack gas velocity for the Method 1 equal-area sector closest to the wall, i.e., the stack gas point velocity value, adjusted for wall effects, for the  $j^{\text{th}}$  Method 1 equal-area sector closest to the wall, actual ft/sec (m/sec);

$\hat{v}_{avg}$  = the average stack gas velocity that accounts for velocity decay near the wall, actual ft/sec (m/sec);

*WAF* = the wall effects adjustment factor derived from  $v_{avg}$  and  $\hat{v}_{avg}$  for a single traverse, dimensionless;

$\hat{v}_{final}$  = the final wall effects-adjusted average stack gas velocity that replaces the unadjusted average stack gas velocity obtained using Method 2, 2F, or 2G for a field test consisting of a single traverse, actual ft/sec (m/sec);

$\bar{W}\bar{A}\bar{F}$  = the wall effects adjustment factor that is applied to the average velocity, unadjusted for wall effects, in order to obtain the final wall effects-adjusted stack gas velocity,  $\hat{v}_{final}$  or  $\hat{v}_{final(k)}$ , dimensionless;

$\hat{v}_{final(k)}$  = the final wall effects-adjusted average stack gas velocity that replaces the unadjusted average stack gas velocity obtained using Method 2, 2F, or 2G on run  $k$  of a RATA or other multiple-run field test procedure, actual ft/sec (m/sec);

$v_{avg(k)}$  = the average stack gas velocity, obtained on run  $k$  of a RATA or other multiple-run procedure, unadjusted for velocity decay near the wall, actual ft/sec (m/sec);

$k$  = index of runs in a RATA or other multiple-run procedure.

12.3 Calculate the average stack gas velocity that does not account for velocity decay near the wall ( $v_{avg}$ ) using Equation 2H-5.

$$v_{\text{avg}} = \frac{\left( \sum_{i=1}^{n-4} vi_i + \sum_{j=1}^4 ve_j \right)}{n} \quad \text{Eq. 2H-5}$$

(Note that  $v_{\text{avg}}$  in Equation 2H-5 is the same as  $v_{(\text{avg})}$  in Equations 2F-9 and 2G-8 in Methods 2F and 2G, respectively.)

For a 16-point traverse, Equation 2H-5 may be written as follows:

$$v_{\text{avg}} = \frac{\left( \sum_{i=1}^{12} vi_i + \sum_{j=1}^4 ve_j \right)}{16} \quad \text{Eq. 2H-6}$$

12.4 Calculate the replacement velocity,  $\bar{v}_e$ , for each of the four Method 1 equal-area sectors closest to the wall using the procedures described in sections 12.4.1 through 12.4.8. Forms 2H-1 and 2H-2 provide sample

tables that may be used in either hardcopy or spreadsheet format to perform the calculations described in sections 12.4.1 through 12.4.8. Forms 2H-3 and 2H-4 provide examples of Form 2H-1 filled in for partial and complete wall effects traverses.

12.4.1 Calculate the average velocity (designated the "decay velocity,"  $v_{\text{dec}_d}$ ) for each sub-sector located between the wall and  $d_{\text{last}}$  (see Figure 2H-3) using Equation 2H-7.

$$v_{\text{dec}_d} = \frac{v_{d-1} + v_d}{2} \quad \text{Eq. 2H-7}$$

For each line in column A of Form 2H-1 or 2H-2 that contains a value of  $d$ , enter the corresponding calculated value of  $v_{\text{dec}_d}$  in column C.

12.4.2 Calculate the cross-sectional area between the wall and the first 1-in. incremented wall effects traverse point and between successive 1-in. incremented wall effects traverse points, from the wall to  $d_{\text{last}}$  (see Figure 2H-3), using Equation 2H-8.

$$A_d = \frac{1}{4} \pi(r-d+1)^2 - \frac{1}{4} \pi(r-d)^2 \quad \text{Eq. 2H-8}$$

For each line in column A of Form 2H-1 or 2H-2 that contains a value of  $d$ , enter the value of the expression  $\frac{1}{4} \pi(r-d+1)^2$  in column D, the value of the expression  $\frac{1}{4} \pi(r-d)^2$  in column E, and the value of  $A_d$  in column F. Note that Equation 2H-8 is designed for use only with English units (in.). If metric units (cm) are used, the first term,  $\frac{1}{4} \pi(r-d+1)^2$ , must be changed to  $\frac{1}{4} \pi(r-d+2.5)^2$ . This change must also be made in column D of Form 2H-1 or 2H-2.

12.4.3 Calculate the volumetric flow through each cross-sectional area derived in

section 12.4.2 by multiplying the values of  $v_{\text{dec}_d}$ , derived according to section 12.4.1, by the cross-sectional areas derived in section 12.4.2 using Equation 2H-9.

$$Q_d = v_{\text{dec}_d} \times A_d \quad \text{Eq. 2H-9}$$

For each line in column A of Form 2H-1 or 2H-2 that contains a value of  $d$ , enter the corresponding calculated value of  $Q_d$  in column G.

12.4.4 Calculate the total volumetric flow through all sub-sectors located between the wall and  $d_{\text{last}}$ , using Equation 2H-10.

$$Q_{d_1 \rightarrow d_{\text{last}}} = \sum_{d=1}^{d_{\text{last}}} Q_d \quad \text{Eq. 2H-10}$$

Enter the calculated value of  $Q_{d_1 \rightarrow d_{\text{last}}}$  in line 3 of column G of Form 2H-1 or 2H-2.

12.4.5 Calculate the cross-sectional area of the sub-sector located between  $d_{\text{last}}$  and the

interior edge of the Method 1 equal-area sector (e.g., sub-sector  $A_{\text{drem}}$  shown in Figures 2H-3 and 2H-4) using Equation 2H-11.

$$A_{\text{drem}} = \frac{1}{4} \pi(r-d_{\text{last}})^2 - \frac{p-2}{4p} \pi(r)^2 \quad \text{Eq. 2H-11}$$

For a 16-point traverse (eight points per diameter), Equation 2H-11 may be written as follows:

$$A_{drem} = \frac{1}{4}\pi(r-d_{last})^2 - \frac{3}{16}\pi(r)^2 \quad \text{Eq. 2H-12}$$

Enter the calculated value of  $A_{drem}$  in line 4b of column G of Form 2H-1 or 2H-2.

12.4.6 Calculate the volumetric flow for the sub-sector located between  $d_{last}$  and the interior edge of the Method 1 equal-area sector, using Equation 2H-13.

$$Q_{drem} = v_{drem} \times A_{drem} \quad \text{Eq. 2H-13}$$

In Equation 2H-13,  $v_{drem}$  is either (1) the measured velocity value at  $d_{rem}$  or (2) the measured velocity at  $d_{last}$ , if the distance between  $d_{rem}$  and  $d_{last}$  is less than or equal to  $\frac{1}{2}$  in. (12.7 mm) and no velocity measurement is taken at  $d_{rem}$  (see section 8.2.4.2). Enter the calculated value of  $Q_{drem}$  in line 4c of column G of Form 2H-1 or 2H-2.

12.4.7 Calculate the total volumetric flow for the Method 1 equal-area sector closest to the wall, using Equation 2H-14.

$$Q_T = Q_{d_1 \rightarrow d_{last}} + Q_{drem} \quad \text{Eq. 2H-14}$$

Enter the calculated value of  $Q_T$  in line 5a of column G of Form 2H-1 or 2H-2.

12.4.8 Calculate the wall effects-adjusted replacement velocity value for the Method 1 equal-area sector closest to the wall, using Equation 2H-15.

$$\hat{v}e_j = \frac{Q_T}{\frac{1}{2p}\pi(r)^2} \quad \text{Eq. 2H-15}$$

For a 16-point traverse (eight points per diameter), Equation 2H-15 may be written as follows:

$$\hat{v}e_j = \frac{Q_T}{\frac{1}{16}\pi(r)^2} \quad \text{Eq. 2H-16}$$

Enter the calculated value of  $\hat{v}e_j$  in line 5B of column G of Form 2H-1 or 2H-2.

12.5 Calculate the wall effects-adjusted average velocity,  $\hat{v}_{avg}$ , by replacing the four values of  $v_{e_j}$  shown in Equation 2H-5 with the four wall effects-adjusted replacement velocity values,  $\hat{v}e_j$ , calculated according to section 12.4.8, using Equation 2H-17.

$$\hat{v}_{avg} = \frac{\left( \sum_{i=1}^{n-4} v_{i_1} + \sum_{j=1}^4 \hat{v}e_j \right)}{n} \quad \text{Eq. 2H-17}$$

For a 16-point traverse, Equation 2H-17 may be written as follows:

$$\hat{v}_{avg} = \frac{\left( \sum_{i=1}^{12} v_{i_1} + \sum_{j=1}^4 \hat{v}e_j \right)}{16} \quad \text{Eq. 2H-18}$$

12.6 Calculate the wall effects adjustment factor, WAF, using Equation 2H-19.

$$\text{WAF} = \frac{\hat{v}_{avg}}{v_{avg}} \quad \text{Eq. 2H-19}$$

12.6.1 Partial wall effects traverse. If a partial wall effects traverse (see section 8.2.2) is conducted, the value obtained from Equation 2H-19 is acceptable and may be reported as the wall effects adjustment factor provided that the value is greater than or equal to 0.9800. If the value is less than 0.9800, it shall not be used and a wall effects adjustment factor of 0.9800 may be used instead.

12.6.2 Complete wall effects traverse. If a complete wall effects traverse (see section 8.2.3) is conducted, the value obtained from Equation 2H-19 is acceptable and may be reported as the wall effects adjustment factor provided that the value is greater than or equal to 0.9700. If the value is less than 0.9700, it shall not be used and a wall effects adjustment factor of 0.9700 may be used instead. If the wall effects adjustment factor for a particular stack or duct is less than 0.9700, the tester may (1) repeat the wall effects test, taking measurements at more Method 1 traverse points and (2) recalculate the wall effects adjustment factor from these measurements, in an attempt to obtain a wall effects adjustment factor that meets the 0.9700 specification and completely characterizes the wall effects.

12.7 Applying a Wall Effects Adjustment Factor. A default wall effects adjustment factor, as specified in section 8.1, or a calculated wall effects adjustment factor meeting the requirements of section 12.6.1 or 12.6.2

may be used to adjust the average stack gas velocity obtained using Methods 2, 2F, or 2G to take into account velocity decay near the wall of circular stacks or ducts. Default wall effects adjustment factors specified in section 8.1 and calculated wall effects adjustment factors that meet the requirements of section 12.6.1 and 12.6.2 are summarized in Table 2H-2.

12.7.1 Single-run tests. Calculate the final wall effects-adjusted average stack gas velocity for field tests consisting of a single traverse using Equation 2H-20.

$$\hat{v}_{\text{final}} = \overline{\text{WAF}} \times v_{\text{avg}} \quad \text{Eq. 2H-20}$$

The wall effects adjustment factor, WAF, shown in Equation 2H-20, may be (1) a default wall effects adjustment factor, as specified in section 8.1, or (2) a calculated adjustment factor that meets the specifications in sections 12.6.1 or 12.6.2. If a calculated adjustment factor is used in Equation 2H-20, the factor must have been obtained during the same traverse in which  $v_{\text{avg}}$  was obtained.

12.7.2 RATA or other multiple run test procedure. Calculate the final wall effects-adjusted average stack gas velocity for any run  $k$  of a RATA or other multiple-run procedure using Equation 2H-21.

$$\hat{v}_{\text{final}(k)} = \overline{\text{WAF}} \times v_{\text{avg}(k)} \quad \text{Eq. 2H-21}$$

The wall effects adjustment factor,  $\overline{\text{WAF}}$ , shown in Equation 2H-21 may be (1) a default wall effects adjustment factor, as specified in section 8.1; (2) a calculated adjustment factor (meeting the specifications in sections 12.6.1 or 12.6.2) obtained from any single run of the RATA that includes run  $k$ ; or (3) the arithmetic average of more than one WAF (each meeting the specifications in sections 12.6.1 or 12.6.2) obtained through wall effects testing conducted during several runs of the RATA that includes run  $k$ . If wall effects adjustment factors (meeting the specifications in sections 12.6.1 or 12.6.2) are determined for more than one RATA run, the arithmetic average of all of the resulting calculated wall effects adjustment factors must be used as the value of  $\overline{\text{WAF}}$  and applied to all runs of that RATA. If a calculated, not a default, wall effects adjustment factor is used in Equation 2H-21, the average velocity unadjusted for wall effects,  $v_{\text{avg}(k)}$  must be obtained from runs in which the number of Method 1 traverse points sampled does not exceed the number of Method 1 traverse points in the runs used to derive the wall effects adjustment factor,  $\overline{\text{WAF}}$ , shown in Equation 2H-21.

12.8 Calculating Volumetric Flow Using Final Wall Effects-Adjusted Average Velocity Value. To obtain a stack gas flow rate that accounts for velocity decay near the wall of circular stacks or ducts, replace  $v_s$  in Equation 2-10 in Method 2, or  $v_{\text{a(avg)}}$  in Equations 2F-10 and 2F-11 in Method 2F, or  $v_{\text{a(avg)}}$  in Equations 2G-9 and 2G-10 in Method 2G with one of the following.

12.8.1 For single-run test procedures, use the final wall effects-adjusted average stack gas velocity,  $\hat{v}_{\text{final}}$ , calculated according to Equation 2H-20.

12.8.2 For RATA and other multiple run test procedures, use the final wall effects-adjusted average stack gas velocity,  $\hat{v}_{\text{final}(k)}$ , calculated according to Equation 2H-21.

13.0 Method Performance [Reserved]

14.0 Pollution Prevention [Reserved]

15.0 Waste Management [Reserved]

16.0 Reporting

16.1 Field Test Reports. Field test reports shall be submitted to the Agency according to the applicable regulatory requirements. When Method 2H is performed in conjunction with Method 2, 2F, or 2G to derive a wall effects adjustment factor, a single consolidated Method 2H/2F (or 2H/2G) field test report should be prepared. At a minimum, the consolidated field test report should contain (1) all of the general information, and data for Method 1 points, specified in section 16.0 of Method 2F (when Method 2H is used in conjunction with Method 2F) or section 16.0 of Method 2G (when Method 2H is used in conjunction with Method 2 or 2G) and (2) the additional general information, and data for Method 1 points and wall effects points, specified in this section (some of which are included in section 16.0 of Methods 2F and 2G and are repeated in this section to ensure complete reporting for wall effects testing).

16.1.1 Description of the source and site. The field test report should include the descriptive information specified in section 16.1.1 of Method 2F (when using Method 2F) or 2G (when using either Method 2 or 2G). It should also include a description of the stack or duct's construction material along with the diagram showing the dimensions of the stack or duct at the test port elevation prescribed in Methods 2F and 2G. The diagram should indicate the location of all wall effects traverse points where measurements were taken as well as the Method 1 traverse points. The diagram should provide a unique identification number for each wall effects and Method 1 traverse point, its distance from the wall, and its location relative to the probe entry ports.

16.1.2 Field test forms. The field test report should include a copy of Form 2H-1, 2H-2, or an equivalent for each Method 1 exterior equal-area sector.

16.1.3 Field test data. The field test report should include the following data for the Method 1 and wall effects traverse.

16.1.3.1 Data for each traverse point. The field test report should include the values

specified in section 16.1.3.2 of Method 2F (when using Method 2F) or 2G (when using either Method 2 or 2G) for each Method 1 and wall effects traverse point. The provisions of section 8.4.2 of Method 2H apply to the temperature measurements reported for wall effects traverse points. For each wall effects and Method 1 traverse point, the following values should also be included in the field test report.

(a) Traverse point identification number for each Method 1 and wall effects traverse point.

(b) Probe type.

(c) Probe identification number.

(d) Probe velocity calibration coefficient (i.e.,  $C_p$  when Method 2 or 2G is used;  $F_2$  when Method 2F is used).

For each Method 1 traverse point in an exterior equal-area sector, the following additional value should be included.

(e) Calculated replacement velocity,  $\hat{v}_{e,r}$ , accounting for wall effects.

16.1.3.2 Data for each run. The values specified in section 16.1.3.3 of Method 2F (when using Method 2F) or 2G (when using either Method 2 or 2G) should be included in the field test report once for each run. The provisions of section 12.8 of Method 2H apply for calculating the reported gas volumetric flow rate. In addition, the following Method 2H run values should also be included in the field test report.

(a) Average velocity for run, accounting for wall effects,  $\hat{v}_{avg}$ .

(b) Wall effects adjustment factor derived from a test run, WAF.

16.1.3.3 Data for a complete set of runs. The values specified in section 16.1.3.4 of Method 2F (when using Method 2F) or 2G (when using either Method 2 or 2G) should be included in the field test report once for each complete set of runs. In addition, the field test report should include the wall effects adjustment factor,  $\bar{WAF}$ , that is applied in accordance with section 12.7.1 or 12.7.2 to obtain the final wall effects-adjusted average stack gas velocity  $\hat{v}_{final}$  or  $\hat{v}_{final,k}$ .

16.1.4 Quality assurance and control. Quality assurance and control procedures, specifically tailored to wall effects testing, should be described.

16.2 Reporting a Default Wall Effects Adjustment Factor. When a default wall effects adjustment factor is used in accordance with section 8.1 of this method, its value and a description of the stack or duct's construction material should be reported in lieu of submitting a test report.

#### 17.0 References.

(1) 40 CFR Part 60, Appendix A, Method 1—Sample and velocity traverses for stationary sources.

(2) 40 CFR Part 60, Appendix A, Method 2—Determination of stack gas velocity and volumetric flow rate (Type S pitot tube).

(3) 40 CFR Part 60, Appendix A, Method 2F—Determination of stack gas velocity and volumetric flow rate with three-dimensional probes.

(4) 40 CFR Part 60, Appendix A, Method 2G—Determination of stack gas velocity and volumetric flow rate with two-dimensional probes.

(5) 40 CFR Part 60, Appendix A, Method 3—Gas analysis for carbon dioxide, oxygen, excess air, and dry molecular weight.

(6) 40 CFR Part 60, Appendix A, Method 3A—Determination of oxygen and carbon dioxide concentrations in emissions from stationary sources (instrumental analyzer procedure).

(7) 40 CFR Part 60, Appendix A, Method 4—Determination of moisture content in stack gases.

(8) Emission Measurement Center (EMC) Approved Alternative Method (ALT-011) "Alternative Method 2 Thermocouple Calibration Procedure."

(9) The Cadmus Group, Inc., 1998, "EPA Flow Reference Method Testing and Analysis: Data Report, Texas Utilities, DeCordova Steam Electric Station, Volume I: Test Description and Appendix A (Data Distribution Package)," EPA/430-R-98-015a.

(10) The Cadmus Group, Inc., 1998, "EPA Flow Reference Method Testing and Analysis: Data Report, Texas Utilities, Lake Hubbard Steam Electric Station, Volume I: Test Description and Appendix A (Data Distribution Package)," EPA/430-R-98-017a.

(11) The Cadmus Group, Inc., 1998, "EPA Flow Reference Method Testing and Analysis: Data Report, Pennsylvania Electric Co., G.P.U. Genco Homer City Station: Unit 1, Volume I: Test Description and Appendix A (Data Distribution Package)," EPA/430-R-98-018a.

(12) The Cadmus Group, Inc., May 1999, "EPA Flow Reference Method Testing and Analysis: Findings Report," EPA/430-R-99-009.

(13) The Cadmus Group, Inc., 1997, "EPA Flow Reference Method Testing and Analysis: Wind Tunnel Experimental Results," EPA/430-R-97-013.

(14) National Institute of Standards and Technology, 1998, "Report of Special Test of Air Speed Instrumentation, Four Prandtl Probes, Four S-Type Probes, Four French Probes, Four Modified Kiel Probes," Prepared for the U.S. Environmental Protection Agency under IAG No. DW13938432-01-0.

(15) National Institute of Standards and Technology, 1998, "Report of Special Test of Air Speed Instrumentation, Five Autoprobes," Prepared for the U.S. Environmental Protection Agency under IAG No. DW13938432-01-0.

(16) National Institute of Standards and Technology, 1998, "Report of Special Test of Air Speed Instrumentation, Eight Spherical Probes." Prepared for the U.S. Environmental Protection Agency under IAG No. DW13938432-01-0.

(17) National Institute of Standards and Technology, 1998, "Report of Special Test of Air Speed Instrumentation, Four DAT Probes." Prepared for the U.S. Environmental Protection Agency under IAG No. DW13938432-01-0.

(18) Massachusetts Institute of Technology (MIT), 1998, "Calibration of Eight Wind Speed Probes Over a Reynolds Number Range of 46,000 to 725,000 per Foot, Text and

Summary Plots," Plus Appendices, WBWT-TR-1317. Prepared for The Cadmus Group, Inc., under EPA Contract 68-W6-0050, Work Assignment 0007AA-3.

(19) Fossil Energy Research Corporation, Final Report, "Velocity Probe Tests in Non-axial Flow Fields," November 1998, Prepared for the U.S. Environmental Protection Agency.

(20) Fossil Energy Research Corporation, "Additional Swirl Tunnel Tests: E-DAT and T-DAT Probes," February 24, 1999, Technical Memorandum Prepared for U.S. Environmental Protection Agency, P.O. No. 7W-1193-NALX.

**Table 2H-1. Distance from the Wall for the Interior Boundary,  $d_b$ , of a Method 1 Exterior Equal-Area Sector as a Function of the Stack or Duct Radius,  $r$ , and Number of Method 1 Traverse Points**

Number of Method 1 Traverse Points	$d_b$
16	$0.134 \times r$
20	$0.106 \times r$
24	$0.087 \times r$
28	$0.074 \times r$
32	$0.065 \times r$
36	$0.057 \times r$
40	$0.051 \times r$
44	$0.047 \times r$
48	$0.043 \times r$

**Table 2H-2 Default and Minimum Acceptable Calculated Wall Effects Adjustment Factors**

		Brick and Mortar Stacks	All Other Stacks and Ducts
<b>Default WAF</b>		0.9900	0.9950
<b>Minimum Acceptable WAF</b>	<b>Partial Traverse</b>	0.9800	
	<b>Complete Traverse</b>	0.9700	

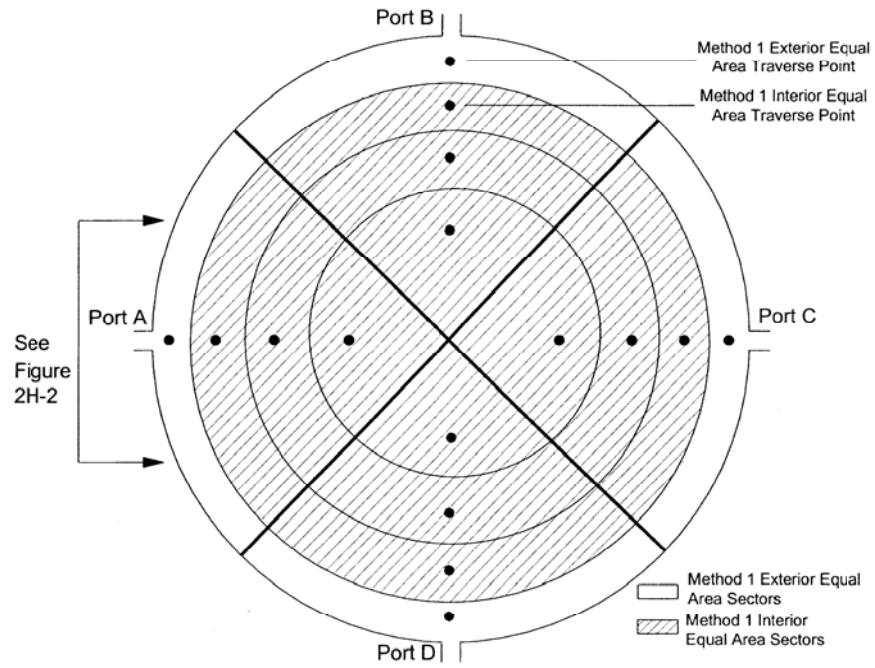


Figure 2H-1. Method 1 exterior and interior equal-area sectors with traverse points indicated.

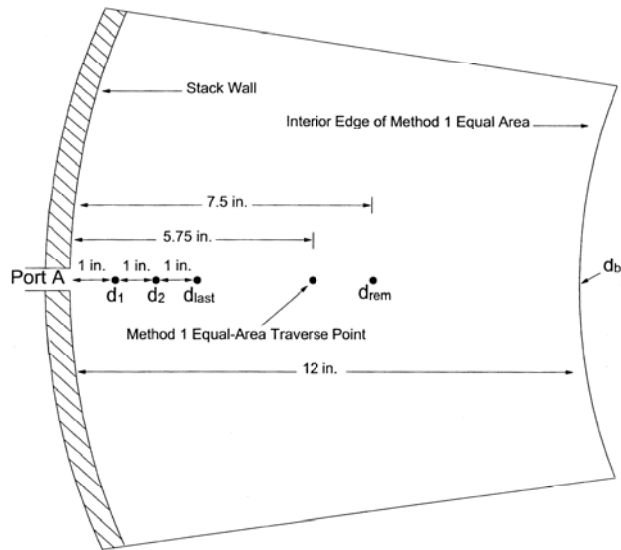
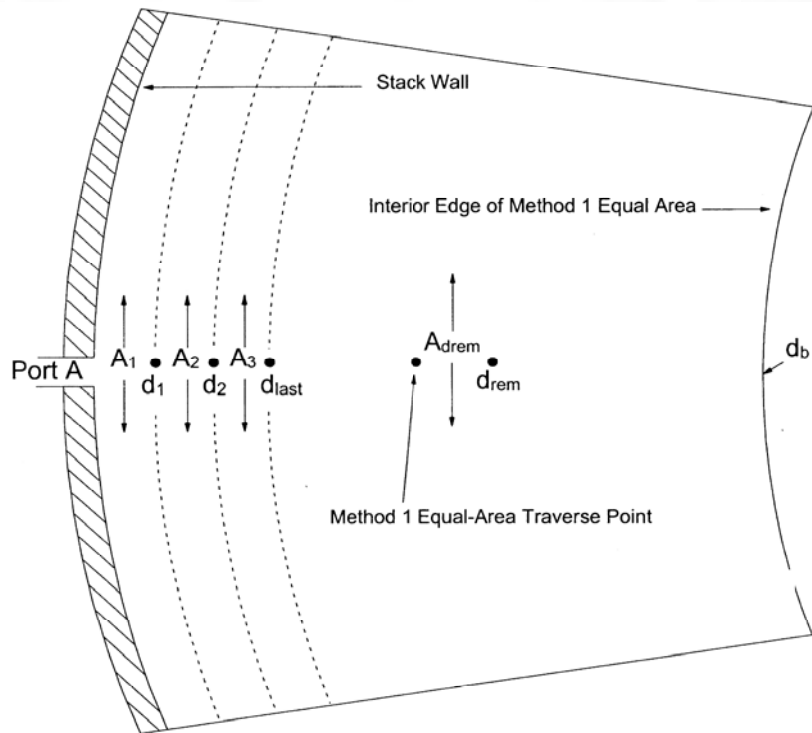


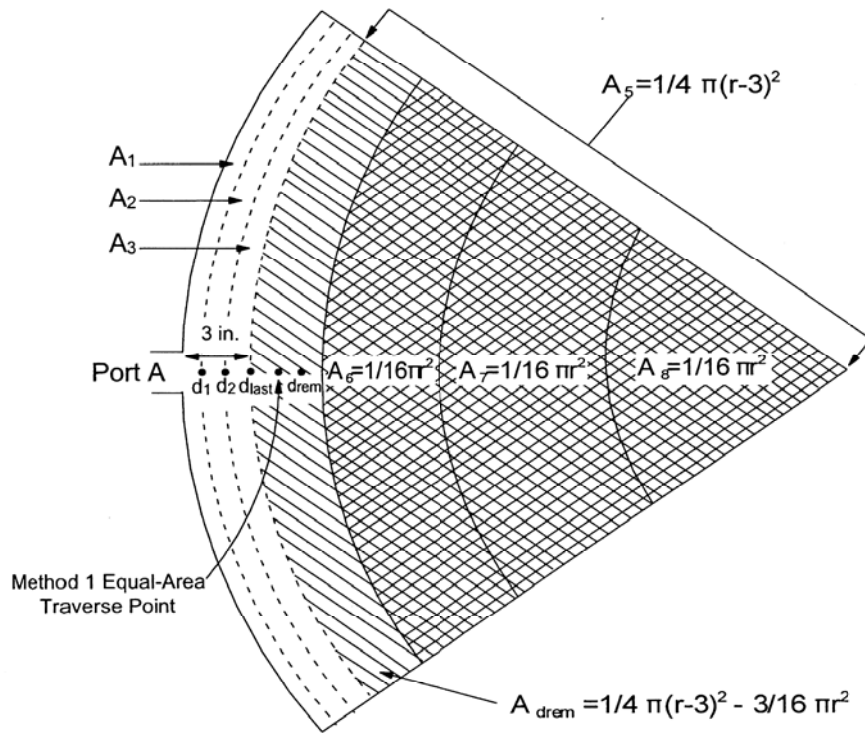
Figure 2H-2. Figure showing part of a Method 1 equal-area sector closest to the stack wall with three illustrative wall effects points at 1 in. intervals, the Method 1 equal-area traverse point, and  $d_{rem}$  for a 15 ft diameter stack.<sup>1</sup>

<sup>1</sup> Metric equivalents of English units used in Figure 2H-2 are as follows: 1 in. = 2.5 cm; 5.75 in. = 14.6 cm; 7.5 in. = 19.0 cm; 12 in. = 30.5 cm; and 15 ft = 4.6 m.





**Figure 2H-3.** Figure showing part of a Method 1 equal-area sector closest to the stack wall with three illustrative sub-sectors between the stack wall and  $d_{last}$  and the sub-sector represented by  $d_{rem}$ .  $A_1$  is the area between the stack wall and  $d_1$ ,  $A_2$  is the area between  $d_1$  and  $d_2$ ,  $A_3$  is the area between  $d_2$  and  $d_{last}$ , and  $A_{drem}$  is the area between  $d_{last}$  and the interior edge of the Method 1 equal-area sector.



**Figure 2H-4.** Figure illustrating the calculations in Equation 2H-12 used to calculate the cross sectional area of the sub-sector between  $d_{last}$  and the interior edge of the Method 1 sector closest to the stack wall ( $A_{drem}$ ) for a 16-point Method 1 traverse. The Method 1 equal-area traverse point and four wall effects traverse points ( $d_1$ ,  $d_2$ ,  $d_{last}$ , and  $d_{rem}$ ) within the Method 1 sector closest to the stack wall are also shown.<sup>1</sup>

<sup>1</sup> All dimensions are given in in. Metric equivalents (in cm) are as follows: 3 in. = 7.6 cm;  $A_5 = 1/4 \pi (r-7.6)^2$ ; and  $A_{drem} = 1/4 \pi (r-7.6)^2 - 3/16 \pi r^2$ .

**Form 2H-1. Calculation of Wall Effects Replacement Velocity Values (16-Point Method 1 Traverse)**

1<sup>st</sup> Probe Type/ID/Pts. Sampled: \_\_\_\_\_ Tester(s): \_\_\_\_\_

2<sup>nd</sup> Probe Type/ID/Pts. Sampled: \_\_\_\_\_ Affiliation: \_\_\_\_\_

Entry Port ID (e.g., A, B, C, or D): \_\_\_\_\_

1. Diameter of the stack or duct (ft)		Radius, <i>r</i> , of the stack or duct (in.) (= diameter × 6)				
2. Location (column A), measured and decay velocities (columns B and C), and volumetric flow (column G) associated with each successive wall effects traverse point.						
(A)	(B)	(C)	(D)   (E)		(F)	(G)
Distance ( <i>d</i> ) from Wall	Measured Velocity ( <i>v<sub>d</sub></i> ) at Distance <i>d</i>	Decay Velocity ( <i>v<sub>dec,d</sub></i> )	Intermediate Calculations		Area of Sub-sector ( <i>A<sub>d</sub></i> )	Volumetric Flow in Sub-sector ( <i>Q<sub>d</sub></i> )
		$\frac{v_{d-1} + v_d}{2}$ Note: <i>v<sub>0</sub></i> = 0	$\frac{1}{4}\pi[r-d+1]^2$	$\frac{1}{4}\pi[r-d]^2$	(Col. D - Col. E)	(Col. C × Col. F)
(in.)	(ft/sec)	(ft/sec)	(in. <sup>2</sup> )	(in. <sup>2</sup> )	(in. <sup>2</sup> )	(ft-in. <sup>2</sup> /sec)
<i>d</i> = 1						
<i>d</i> = 2						
...						
<i>d<sub>last</sub></i>						
Note: <i>d<sub>last</sub></i> ≤ 0.1340 <i>r</i> , where <i>r</i> is the radius of the stack or duct. See section 8.2.2.3 of the method.						
3. Total volumetric flow for all sub-sectors located between stack wall and <i>d<sub>last</sub></i> (total Col. G).						
4. Volumetric flow for remainder of the Method 1 equal-area sector.						
a. Velocity measurement at distance <i>d<sub>rem</sub></i> from stack wall ( <i>v<sub>drem</sub></i> ). (If <i>d<sub>rem</sub></i> - <i>d<sub>last</sub></i> < ½ in., then no measurement at <i>d<sub>rem</sub></i> is necessary. Enter the velocity at <i>d<sub>last</sub></i> on this line.)						
b. Total area in remainder of Method 1 equal-area segment ( <i>A<sub>drem</sub></i> ). Subtract $\frac{3}{16}\pi(r)^2$ from last entry in item 2, column E, and enter the result on this line.						
c. Multiply values on lines 4a and 4b. ( <i>Q<sub>drem</sub></i> )						
5. Wall effects-adjusted velocity in the Method 1 equal-area sector.						
a. Add the values on lines 3 and 4c. ( <i>Q<sub>r</sub></i> )						
b. Divide line 5a by $\frac{1}{16}\pi(r)^2$ . The resulting value is one of four "replacement" point velocity values adjusted for wall effects, <i>v<sub>e</sub></i> , as derived in Equation 2H-16.						
6. Substitute the value shown in 5b for the unadjusted velocity value in the Method 1 sector. (See Eq. 2H-18.)						

**Notes:** 1. Column B: If no measurement is taken at distance *d*, enter the velocity value obtained at the first subsequent traverse point where a measurement was taken, followed by the letters "NM". See section 8.7.1.2.  
 2. For clarity, only English units are shown in this form. Following are metric equivalents of the English units used in the form. In row 2, column A: 1 in. = 2.5 cm; 2 in. = 5.1 cm. In row 2, column D: If metric units (cm) are used, the term  $\frac{1}{4}\pi(r-d+1)^2$  must be changed to  $\frac{1}{4}\pi(r-d+2.5)^2$ . In row 4a: ½ in. = 12.7 mm. Throughout the form, the metric equivalents of in., in.<sup>2</sup>, ft, ft/sec, and ft-in<sup>2</sup>/sec are cm, cm<sup>2</sup>, m, m/sec, and m-cm<sup>2</sup>/sec, respectively.

**Form 2H-2. Calculation of Wall Effects Replacement Velocity Values (Any Method 1 Traverse ≥ 16 Points)**

1<sup>st</sup> Probe Type/ID/Pts. Sampled: \_\_\_\_\_ Tester(s): \_\_\_\_\_

2<sup>nd</sup> Probe Type/ID/Pts. Sampled: \_\_\_\_\_ Affiliation: \_\_\_\_\_

Entry Port ID (e.g., A, B, C, or D): \_\_\_\_\_

1. Diameter of the stack or duct (ft)		Radius, <i>r</i> , of the stack or duct (in.) (= diameter × 6)				
2. Location (Column A), measured and decay velocities (Columns B and C), and volumetric flow (Column G) associated with each successive wall effects traverse point.						
(A)	(B)	(C)	(D)	(E)	(F)	(G)
Distance ( <i>d</i> ) from Wall	Measured Velocity ( <i>v<sub>d</sub></i> ) at Distance <i>d</i>	Decay Velocity ( <i>v<sub>dec,d</sub></i> )	Intermediate Calculations		Area of Sub-sector ( <i>A<sub>d</sub></i> )	Volumetric Flow in Sub-sector ( <i>Q<sub>d</sub></i> )
		$\frac{v_{d-1} + v_d}{2}$ Note: <i>v<sub>0</sub></i> = 0	$\frac{2}{p} \pi [r-d+1]^2$	$\frac{2}{p} \pi [r-d]^2$	(Col. D - Col. E)	(Col. C × Col. F)
(in.)	(ft/sec)	(ft/sec)	(in. <sup>2</sup> )	(in. <sup>2</sup> )	(in. <sup>2</sup> )	(ft-in. <sup>3</sup> /sec)
<i>d</i> = 1						
<i>d</i> = 2						
...						
<i>d<sub>last</sub></i>						
Note: <i>d<sub>last</sub></i> ≤ <i>d<sub>0</sub></i> , as defined in section 8.2.2.3 of the method.						
3. Total volumetric flow for all sub-sectors located between stack wall and <i>d<sub>last</sub></i> (total Col. G).						
4. Volumetric flow for remainder of the Method 1 equal-area sector.						
a. Velocity measurement at distance <i>d<sub>rem</sub></i> from stack wall ( <i>v<sub>drem</sub></i> ). (If <i>d<sub>rem</sub></i> - <i>d<sub>last</sub></i> < ½ in., then no measurement at <i>d<sub>rem</sub></i> is necessary. Enter the velocity at <i>d<sub>last</sub></i> on this line.)						
b. Total area in remainder of Method 1 equal-area segment ( <i>A<sub>drem</sub></i> ). Subtract $\left(\frac{p-2}{4p}\right) \pi (r)^2$ from last entry in item 2, column E, and enter the result on this line.						
c. Multiply values on lines 4a and 4b. ( <i>Q<sub>drem</sub></i> )						
5. Wall effects-adjusted velocity in the Method 1 near-wall equal-area segment.						
a. Add the values on lines 3 and 4. ( <i>Q<sub>r</sub></i> )						
b. Divide line 5a by $\left(\frac{1}{2p}\right) \pi (r)^2$ . The resulting value is one of four "replacement" point velocity values adjusted for wall effects, $\hat{v}_e$ , as derived in Equation 2H-15.						
6. Substitute the value shown in 5b for the unadjusted velocity value in the Method 1 sector. (See Eq. 2H-17.)						

Notes: 1. Column B: If no measurement is taken at distance *d*, enter the velocity value obtained at the first subsequent traverse point where a measurement was taken, followed by the letters "NM". See section 8.7.1.2.  
 2. For clarity, only English units are shown in this form. Following are metric equivalents of the English units used in the form. In row 2, column A: 1 in. = 2.5 cm; 2 in. = 5.1 cm. In row 2, column D: If metric units (cm) are used, the term  $\frac{1}{4} \pi (r-d+1)^2$  must be changed to  $\frac{1}{4} \pi (r-d+2.5)^2$ . In row 4a: ½ in. = 12.7 mm. Throughout the form, the metric equivalents of in., in.<sup>2</sup>, ft, ft/sec, and ft-in.<sup>3</sup>/sec are cm, cm<sup>2</sup>, m, m/sec, and m-cm<sup>3</sup>/sec, respectively.

**Form 2H-3. Calculation of Replacement Velocity Values for a Method 1 Equal-Area Sector Closest to the Stack Wall for a 16-Point Method 1 Traverse, Using a Partial Wall Effects Traverse**

1<sup>st</sup> Probe Type/ID/Pts. Sampled: Type S Straight-up/S-13/All Tester(s): Test Team III

2<sup>nd</sup> Probe Type/ID/Pts. Sampled: \_\_\_\_\_ Affiliation: Contractor III

Entry Port ID (e.g., A, B, C, or D): A

1. Diameter of the stack or duct (ft)		24		Radius, <i>r</i> , of the stack or duct (in.) (= diameter × 6)		144	
2. Location (column A), measured and decay velocities (columns B and C), and volumetric flow (column G) associated with each successive wall effects traverse point.							
(A)	(B)	(C)	(D)		(E)	(F)	(G)
Distance ( <i>d</i> ) from Wall	Measured Velocity ( <i>v<sub>d</sub></i> ) at Distance <i>d</i>	Decay Velocity ( <i>v<sub>dec,d</sub></i> )	Intermediate Calculations		Area of Sub-sector ( <i>A<sub>d</sub></i> )	Volumetric Flow in Sub-sector ( <i>Q<sub>d</sub></i> )	
		$\frac{v_{d-1} + v_d}{2}$ Note: <i>v<sub>0</sub></i> = 0	$\frac{1}{4} \pi [r - d + 1]^2$	$\frac{1}{4} \pi [r - d]^2$	(Col. D - Col. E)	(Col. C × Col. F)	
(in.)	(ft/sec)	(ft/sec)	(in. <sup>2</sup> )	(in. <sup>2</sup> )	(in. <sup>2</sup> )	(ft-in. <sup>2</sup> /sec)	
<i>d</i> = 1	51.71 NM	25.85	16,286.00	16,060.59	225.41	5,827.47	
<i>d</i> = 2	51.71 NM	51.71	16,060.59	15,836.76	223.84	11,573.72	
<i>d<sub>last</sub></i> = 3	51.71	51.71	15,836.76	15,614.49	222.27	11,492.51	
3. Total volumetric flow for all sub-sectors located between stack wall and <i>d<sub>last</sub></i> (total Col. G).						28,893.70	
4. Volumetric flow for remainder of the Method 1 equal-area sector.							
a. Velocity measurement at distance <i>d<sub>rem</sub></i> from stack wall ( <i>v<sub>drem</sub></i> ). (If <i>d<sub>rem</sub></i> - <i>d<sub>last</sub></i> < ½ in., then no measurement at <i>d<sub>rem</sub></i> is necessary. Enter the velocity at <i>d<sub>last</sub></i> on this line.)						77.01	
b. Total area in remainder of Method 1 equal-area segment ( <i>A<sub>drem</sub></i> ). Subtract $\frac{3}{16} \pi (r)^2$ from last entry in item 2, column E, and enter the result on this line.						3,399.99	
c. Multiply values on lines 4a and 4b. ( <i>Q<sub>drem</sub></i> )						261,832.90	
5. Wall effects-adjusted velocity in the Method 1 equal-area sector.							
a. Add the values on lines 3 and 4c. ( <i>Q<sub>T</sub></i> )						290,726.61	
b. Divide line 5a by $\frac{1}{16} \pi (r)^2$ . The resulting value is one of four "replacement" point velocity values adjusted for wall effects, $\hat{v}_{e_i}$ , as derived in Equation 2H-16.						71.41	
6. Substitute the value shown in 5b for the unadjusted velocity value in the Method 1 sector. (See Eq. 2H-18.)							

**Form 2H-4 Calculation of Replacement Velocity Values for a Method 1 Equal-Area Sector Closest to the Stack Wall for a 16-Point Method 1 Traverse, Using a Complete Traverse**

1<sup>st</sup> Probe Type/ID/Pts. Sampled: Type S Straight-up/S-13/All Tester(s): Test Team III

2<sup>nd</sup> Probe Type/ID/Pts. Sampled: \_\_\_\_\_ Affiliation: Contractor III

Entry Port ID (e.g., A, B, C, or D): A

1. Diameter of the stack or duct (ft)		24		Radius, <i>r</i> , of the stack or duct (in.) (= diameter × 6)		144	
2. Location (column A), measured and decay velocities (columns B and C), and volumetric flow (column G) associated with each successive wall effects traverse point.							
(A)	(B)	(C)	(D)		(E)	(F)	(G)
Distance ( <i>d</i> ) from Wall	Measured Velocity ( <i>v<sub>d</sub></i> ) at Distance <i>d</i>	Decay Velocity ( <i>v<sub>dec,d</sub></i> )	Intermediate Calculations		Area of Sub-sector ( <i>A<sub>d</sub></i> )	Volumetric Flow in Sub-sector ( <i>Q<sub>d</sub></i> )	
		$\frac{v_{d-1} + v_d}{2}$	$\frac{1}{4}\pi[r-d+1]^2$	$\frac{1}{4}\pi[r-d]^2$	(Col. D - Col. E)	(Col. C × Col. F)	
		Note: <i>v<sub>0</sub></i> = 0					
(in.)	(ft/sec)	(ft/sec)	(in. <sup>2</sup> )	(in. <sup>2</sup> )	(in. <sup>2</sup> )	(ft-in. <sup>2</sup> /sec)	
<i>d</i> = 1	51.71 NM	25.85	16,286.00	16,060.59	225.41	5,827.47	
<i>d</i> = 2	51.71 NM	51.71	16,060.59	15,836.76	223.84	11,573.72	
<i>d</i> = 3	51.71	51.71	15,836.76	15,614.49	222.27	11,492.51	
<i>d</i> = 4	62.26	56.98	15,614.49	15,393.79	220.70	12,576.24	
<i>d</i> = 5	67.16	64.71	15,393.79	15,174.67	219.13	14,179.40	
<i>d</i> = 6	69.44	68.30	15,174.67	14,957.11	217.56	14,858.32	
<i>d</i> = 7	72.63	71.03	14,957.11	14,741.13	215.98	15,341.75	
<i>d</i> = 8	71.37	72.00	14,741.13	14,526.71	214.41	15,437.01	
<i>d</i> = 9	74.37	72.87	14,526.71	14,313.87	212.84	15,510.03	
<i>d</i> = 10	75.80	75.08	14,313.87	14,102.60	211.27	15,863.30	
<i>d</i> = 11	77.15	76.47	14,102.60	13,892.90	209.70	16,035.93	
<i>d<sub>last</sub></i> = 12	78.58	77.86	13,892.90	13,684.77	208.13	16,205.92	
3. Total volumetric flow for all sub-sectors located between stack wall and <i>d<sub>last</sub></i> (total Col. G).						164,901.59	
4. Volumetric flow for remainder of the Method 1 equal-area sector.							
a. Velocity measurement at distance <i>d<sub>rem</sub></i> from stack wall ( <i>v<sub>rem</sub></i> ). (If <i>d<sub>rem</sub></i> - <i>d<sub>last</sub></i> < ½ in., then no measurement at <i>d<sub>rem</sub></i> is necessary. Enter the velocity at <i>d<sub>last</sub></i> on this line.)						78.51	
b. Total area in remainder of Method 1 equal-area segment ( <i>A<sub>rem</sub></i> ). Subtract $\frac{3}{16}\pi(r)^2$ from last entry in item 2, column E, and enter the result on this line.						1,470.26	
c. Multiply values on lines 4a and 4b. ( <i>Q<sub>rem</sub></i> )						115,430.44	
5. Wall effects-adjusted velocity in the Method 1 equal-area sector.							
a. Add the values on lines 3 and 4c. ( <i>Q<sub>r</sub></i> )						280,332.03	
b. Divide line 5a by $\frac{1}{16}\pi(r)^2$ . The resulting value is one of four "replacement" point velocity values adjusted for wall effects, <i>v<sub>e</sub></i> , as derived in Equation 2H-16.						68.85	
6. Substitute the value shown in 5b for the unadjusted velocity value in the Method 1 sector. (See Eq. 2H-18.)							

**METHOD 3—GAS ANALYSIS FOR THE DETERMINATION OF DRY MOLECULAR WEIGHT**

NOTE: This method does not include all of the specifications (e.g., equipment and supplies) and procedures (e.g., sampling) essential to its performance. Some material is in-

corporated by reference from other methods in this part. Therefore, to obtain reliable results, persons using this method should also have a thorough knowledge of Method 1.

*1.0 Scope and Application*

1.1 Analytes.

Analytes	CAS No.	Sensitivity
Oxygen (O <sub>2</sub> ) .....	7782-44-7	2,000 ppmv.
Nitrogen (N <sub>2</sub> ) .....	7727-37-9	N/A.
Carbon dioxide (CO <sub>2</sub> ) .....	124-38-9	2,000 ppmv.
Carbon monoxide (CO) .....	630-08-0	N/A.

1.2 Applicability. This method is applicable for the determination of CO<sub>2</sub> and O<sub>2</sub> concentrations and dry molecular weight of a sample from an effluent gas stream of a fossil-fuel combustion process or other process.

1.3 Other methods, as well as modifications to the procedure described herein, are also applicable for all of the above determinations. Examples of specific methods and modifications include: (1) A multi-point grab sampling method using an Orsat analyzer to analyze the individual grab sample obtained at each point; (2) a method for measuring either CO<sub>2</sub> or O<sub>2</sub> and using stoichiometric calculations to determine dry molecular weight; and (3) assigning a value of 30.0 for dry molecular weight, in lieu of actual measurements, for processes burning natural gas, coal, or oil. These methods and modifications may be used, but are subject to the approval of the Administrator. The method may also be applicable to other processes where it has been determined that compounds other than CO<sub>2</sub>, O<sub>2</sub>, carbon monoxide (CO), and nitrogen (N<sub>2</sub>) are not present in concentrations sufficient to affect the results.

1.4 Data Quality Objectives. Adherence to the requirements of this method will enhance the quality of the data obtained from air pollutant sampling methods.

### 2.0 Summary of Method

2.1 A gas sample is extracted from a stack by one of the following methods: (1) single-point, grab sampling; (2) single-point, integrated sampling; or (3) multi-point, integrated sampling. The gas sample is analyzed for percent CO<sub>2</sub> and percent O<sub>2</sub>. For dry molecular weight determination, either an Orsat or a Fyrite analyzer may be used for the analysis.

### 3.0 Definitions [Reserved]

### 4.0 Interferences

4.1 Several compounds can interfere, to varying degrees, with the results of Orsat or Fyrite analyses. Compounds that interfere with CO<sub>2</sub> concentration measurement include acid gases (*e.g.*, sulfur dioxide, hydrogen chloride); compounds that interfere with O<sub>2</sub> concentration measurement include unsaturated hydrocarbons (*e.g.*, acetone, acetylene), nitrous oxide, and ammonia. Ammonia reacts chemically with the O<sub>2</sub> absorbing so-

lution, and when present in the effluent gas stream must be removed before analysis.

### 5.0 Safety

5.1 Disclaimer. This method may involve hazardous materials, operations, and equipment. This test method may not address all of the safety problems associated with its use. It is the responsibility of the user of this test method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to performing this test method.

#### 5.2 Corrosive Reagents.

5.2.1 A typical Orsat analyzer requires four reagents: a gas-confining solution, CO<sub>2</sub> absorbent, O<sub>2</sub> absorbent, and CO absorbent. These reagents may contain potassium hydroxide, sodium hydroxide, cuprous chloride, cuprous sulfate, alkaline pyrogallic acid, and/or chromous chloride. Follow manufacturer's operating instructions and observe all warning labels for reagent use.

5.2.2 A typical Fyrite analyzer contains zinc chloride, hydrochloric acid, and either potassium hydroxide or chromous chloride. Follow manufacturer's operating instructions and observe all warning labels for reagent use.

### 6.0 Equipment and Supplies

NOTE: As an alternative to the sampling apparatus and systems described herein, other sampling systems (*e.g.*, liquid displacement) may be used, provided such systems are capable of obtaining a representative sample and maintaining a constant sampling rate, and are, otherwise, capable of yielding acceptable results. Use of such systems is subject to the approval of the Administrator.

#### 6.1 Grab Sampling (See Figure 3-1).

6.1.1 Probe. Stainless steel or borosilicate glass tubing equipped with an in-stack or out-of-stack filter to remove particulate matter (a plug of glass wool is satisfactory for this purpose). Any other materials, resistant to temperature at sampling conditions and inert to all components of the gas stream, may be used for the probe. Examples of such materials may include aluminum, copper, quartz glass, and Teflon.

6.1.2 Pump. A one-way squeeze bulb, or equivalent, to transport the gas sample to the analyzer.

#### 6.2 Integrated Sampling (Figure 3-2).

6.2.1 Probe. Same as in section 6.1.1.

6.2.2 Condenser. An air-cooled or water-cooled condenser, or other condenser no greater than 250 ml that will not remove O<sub>2</sub>, CO<sub>2</sub>, CO, and N<sub>2</sub>, to remove excess moisture which would interfere with the operation of the pump and flowmeter.

6.2.3 Valve. A needle valve, to adjust sample gas flow rate.

6.2.4 Pump. A leak-free, diaphragm-type pump, or equivalent, to transport sample gas to the flexible bag. Install a small surge tank between the pump and rate meter to eliminate the pulsation effect of the diaphragm pump on the rate meter.

6.2.5 Rate Meter. A rotameter, or equivalent, capable of measuring flow rate to  $\pm 2$  percent of the selected flow rate. A flow rate range of 500 to 1000 ml/min is suggested.

6.2.6 Flexible Bag. Any leak-free plastic (e.g., Tedlar, Mylar, Teflon) or plastic-coated aluminum (e.g., aluminized Mylar) bag, or equivalent, having a capacity consistent with the selected flow rate and duration of the test run. A capacity in the range of 55 to 90 liters (1.9 to 3.2 ft<sup>3</sup>) is suggested. To leak-check the bag, connect it to a water manometer, and pressurize the bag to 5 to 10 cm H<sub>2</sub>O (2 to 4 in. H<sub>2</sub>O). Allow to stand for 10 minutes. Any displacement in the water manometer indicates a leak. An alternative leak-check method is to pressurize the bag to 5 to 10 cm (2 to 4 in.) H<sub>2</sub>O and allow to stand overnight. A deflated bag indicates a leak.

6.2.7 Pressure Gauge. A water-filled U-tube manometer, or equivalent, of about 30 cm (12 in.), for the flexible bag leak-check.

6.2.8 Vacuum Gauge. A mercury manometer, or equivalent, of at least 760 mm (30 in.) Hg, for the sampling train leak-check.

6.3 Analysis. An Orsat or Fyrite type combustion gas analyzer.

#### 7.0 Reagents and Standards

7.1 Reagents. As specified by the Orsat or Fyrite-type combustion analyzer manufacturer.

7.2 Standards. Two standard gas mixtures, traceable to National Institute of Standards and Technology (NIST) standards, to be used in auditing the accuracy of the analyzer and the analyzer operator technique:

7.2.1. Gas cylinder containing 2 to 4 percent O<sub>2</sub> and 14 to 18 percent CO<sub>2</sub>.

7.2.2. Gas cylinder containing 2 to 4 percent CO<sub>2</sub> and about 15 percent O<sub>2</sub>.

#### 8.0 Sample Collection, Preservation, Storage, and Transport

8.1 Single Point, Grab Sampling Procedure.

8.1.1 The sampling point in the duct shall either be at the centroid of the cross section or at a point no closer to the walls than 1.0 m (3.3 ft), unless otherwise specified by the Administrator.

8.1.2 Set up the equipment as shown in Figure 3-1, making sure all connections ahead of

the analyzer are tight. If an Orsat analyzer is used, it is recommended that the analyzer be leak-checked by following the procedure in section 11.5; however, the leak-check is optional.

8.1.3 Place the probe in the stack, with the tip of the probe positioned at the sampling point. Purge the sampling line long enough to allow at least five exchanges. Draw a sample into the analyzer, and immediately analyze it for percent CO<sub>2</sub> and percent O<sub>2</sub> according to section 11.2.

8.2 Single-Point, Integrated Sampling Procedure.

8.2.1 The sampling point in the duct shall be located as specified in section 8.1.1.

8.2.2 Leak-check (optional) the flexible bag as in section 6.2.6. Set up the equipment as shown in Figure 3-2. Just before sampling, leak-check (optional) the train by placing a vacuum gauge at the condenser inlet, pulling a vacuum of at least 250 mm Hg (10 in. Hg), plugging the outlet at the quick disconnect, and then turning off the pump. The vacuum should remain stable for at least 0.5 minute. Evacuate the flexible bag. Connect the probe, and place it in the stack, with the tip of the probe positioned at the sampling point. Purge the sampling line. Next, connect the bag, and make sure that all connections are tight.

8.2.3 Sample Collection. Sample at a constant rate ( $\pm 10$  percent). The sampling run should be simultaneous with, and for the same total length of time as, the pollutant emission rate determination. Collection of at least 28 liters (1.0 ft<sup>3</sup>) of sample gas is recommended; however, smaller volumes may be collected, if desired.

8.2.4 Obtain one integrated flue gas sample during each pollutant emission rate determination. Within 8 hours after the sample is taken, analyze it for percent CO<sub>2</sub> and percent O<sub>2</sub> using either an Orsat analyzer or a Fyrite type combustion gas analyzer according to section 11.3.

NOTE: When using an Orsat analyzer, periodic Fyrite readings may be taken to verify/confirm the results obtained from the Orsat.

8.3 Multi-Point, Integrated Sampling Procedure.

8.3.1 Unless otherwise specified in an applicable regulation, or by the Administrator, a minimum of eight traverse points shall be used for circular stacks having diameters less than 0.61 m (24 in.), a minimum of nine shall be used for rectangular stacks having equivalent diameters less than 0.61 m (24 in.), and a minimum of 12 traverse points shall be used for all other cases. The traverse points shall be located according to Method 1.

8.3.2 Follow the procedures outlined in sections 8.2.2 through 8.2.4, except for the following: Traverse all sampling points, and sample at each point for an equal length of



time. Record sampling data as shown in Figure 3-3.

9.0 Quality Control

Section	Quality control measure	Effect
8.2	Use of Fyrite to confirm Orsat results	Ensures the accurate measurement of CO <sub>2</sub> and O <sub>2</sub> .
10.1	Periodic audit of analyzer and operator technique.	Ensures that the analyzer is operating properly and that the operator performs the sampling procedure correctly and accurately.
11.3	Replicable analyses of integrated samples.	Minimizes experimental error.

10.0 Calibration and Standardization

10.1 Analyzer. The analyzer and analyzer operator's technique should be audited periodically as follows: take a sample from a manifold containing a known mixture of CO<sub>2</sub> and O<sub>2</sub>, and analyze according to the procedure in section 11.3. Repeat this procedure until the measured concentration of three consecutive samples agrees with the stated value ±0.5 percent. If necessary, take corrective action, as specified in the analyzer users manual.

10.2 Rotameter. The rotameter need not be calibrated, but should be cleaned and maintained according to the manufacturer's instruction.

11.0 Analytical Procedure

11.1 Maintenance. The Orsat or Fyrite-type analyzer should be maintained and operated according to the manufacturers specifications.

11.2 Grab Sample Analysis. Use either an Orsat analyzer or a Fyrite-type combustion gas analyzer to measure O<sub>2</sub> and CO<sub>2</sub> concentration for dry molecular weight determination, using procedures as specified in the analyzer user's manual. If an Orsat analyzer is used, it is recommended that the Orsat leak-check, described in section 11.5, be performed before this determination; however, the check is optional. Calculate the dry molecular weight as indicated in section 12.0. Repeat the sampling, analysis, and calculation procedures until the dry molecular weights of any three grab samples differ from their mean by no more than 0.3 g/g-mole (0.3 lb/lb-mole). Average these three molecular weights, and report the results to the nearest 0.1 g/g-mole (0.1 lb/lb-mole).

11.3 Integrated Sample Analysis. Use either an Orsat analyzer or a Fyrite-type combustion gas analyzer to measure O<sub>2</sub> and CO<sub>2</sub> concentration for dry molecular weight determination, using procedures as specified in the analyzer user's manual. If an Orsat analyzer is used, it is recommended that the Orsat leak-check, described in section 11.5, be performed before this determination; however, the check is optional. Calculate the dry molecular weight as indicated in section 12.0. Repeat the analysis and calculation procedures until the individual dry molecular

weights for any three analyses differ from their mean by no more than 0.3 g/g-mole (0.3 lb/lb-mole). Average these three molecular weights, and report the results to the nearest 0.1 g/g-mole (0.1 lb/lb-mole).

11.4 Standardization. A periodic check of the reagents and of operator technique should be conducted at least once every three series of test runs as outlined in section 10.1.

11.5 Leak-Check Procedure for Orsat Analyzer. Moving an Orsat analyzer frequently causes it to leak. Therefore, an Orsat analyzer should be thoroughly leak-checked on site before the flue gas sample is introduced into it. The procedure for leak-checking an Orsat analyzer is as follows:

11.5.1 Bring the liquid level in each pipette up to the reference mark on the capillary tubing, and then close the pipette stopcock.

11.5.2 Raise the leveling bulb sufficiently to bring the confining liquid meniscus onto the graduated portion of the burette, and then close the manifold stopcock.

11.5.3 Record the meniscus position.

11.5.4 Observe the meniscus in the burette and the liquid level in the pipette for movement over the next 4 minutes.

11.5.5 For the Orsat analyzer to pass the leak-check, two conditions must be met:

11.5.5.1 The liquid level in each pipette must not fall below the bottom of the capillary tubing during this 4-minute interval.

11.5.5.2 The meniscus in the burette must not change by more than 0.2 ml during this 4-minute interval.

11.5.6 If the analyzer fails the leak-check procedure, check all rubber connections and stopcocks to determine whether they might be the cause of the leak. Disassemble, clean, and regrease any leaking stopcocks. Replace leaking rubber connections. After the analyzer is reassembled, repeat the leak-check procedure.

12.0 Calculations and Data Analysis

12.1 Nomenclature.

M<sub>d</sub> = Dry molecular weight, g/g-mole (lb/lb-mole).

%CO<sub>2</sub> = Percent CO<sub>2</sub> by volume, dry basis.

%O<sub>2</sub> = Percent O<sub>2</sub> by volume, dry basis.

%CO = Percent CO by volume, dry basis.

%N<sub>2</sub> = Percent N<sub>2</sub> by volume, dry basis.

0.280 = Molecular weight of N<sub>2</sub> or CO, divided by 100.

0.320 = Molecular weight of O<sub>2</sub> divided by 100.

0.440 = Molecular weight of CO<sub>2</sub> divided by 100.

12.2 Nitrogen, Carbon Monoxide Concentration. Determine the percentage of the gas

that is N<sub>2</sub> and CO by subtracting the sum of the percent CO<sub>2</sub> and percent O<sub>2</sub> from 100 percent.

12.3 Dry Molecular Weight. Use Equation 3-1 to calculate the dry molecular weight of the stack gas.

$$M_d = 0.440(\%CO_2) + 0.320(\%O_2) + 0.280(\%N_2 + \%CO) \quad \text{Eq. 3-1}$$

NOTE: The above Equation 3-1 does not consider the effect on calculated dry molecular weight of argon in the effluent gas. The concentration of argon, with a molecular weight of 39.9, in ambient air is about 0.9 percent. A negative error of approximately 0.4 percent is introduced. The tester may choose to include argon in the analysis using procedures subject to approval of the Administrator.

13.0 Method Performance [Reserved]

14.0 Pollution Prevention [Reserved]

15.0 Waste Management [Reserved]

16.0 References

1. Altshuller, A.P. Storage of Gases and Vapors in Plastic Bags. *International Journal of Air and Water Pollution*, 6:75-81. 1963.

2. Conner, William D. and J.S. Nader. Air Sampling with Plastic Bags. *Journal of the American Industrial Hygiene Association*, 25:291-297. 1964.

3. Burrell Manual for Gas Analysts. Seventh edition. Burrell Corporation, 2223 Fifth Avenue, Pittsburgh, PA. 15219. 1951.

4. Mitchell, W.J. and M.R. Midgett. Field Reliability of the Orsat Analyzer. *Journal of Air Pollution Control Association*, 26:491-495. May 1976.

5. Shigehara, R.T., R.M. Neulicht, and W.S. Smith. Validating Orsat Analysis Data from Fossil Fuel-Fired Units. *Stack Sampling News*, 4(2):21-26. August 1976.

17.0 Tables, Diagrams, Flowcharts, and Validation Data

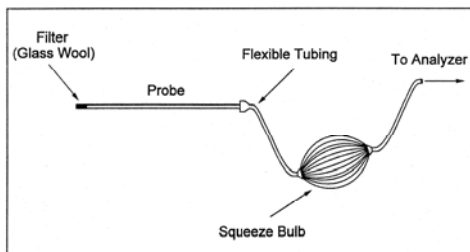


Figure 3-1. Grab-Sampling Train.

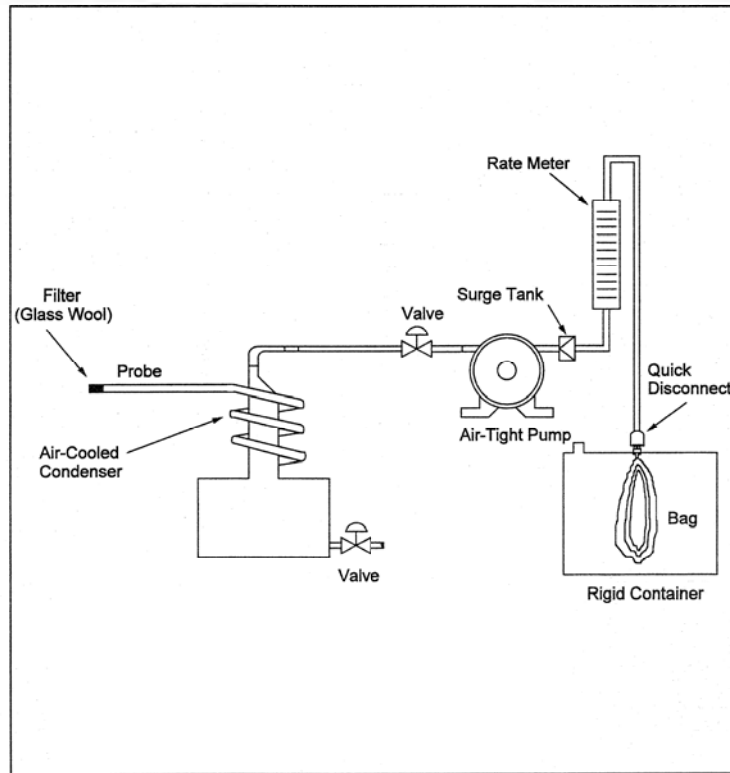


Figure 3-2. Integrated Gas-Sampling Train.

Time	Traverse point	Q (liter/min)	% Deviation <sup>a</sup>
Average			

<sup>a</sup>% Dev. =  $[(Q - Q_{avg}) / Q_{avg}] \times 100$  (Must be  $\leq \pm 10\%$ )

Figure 3-3. Sampling Rate Data

**METHOD 3A—DETERMINATION OF OXYGEN AND CARBON DIOXIDE CONCENTRATIONS IN EMISSIONS FROM STATIONARY SOURCES (INSTRUMENTAL ANALYZER PROCEDURE)**

*1.0 Scope and Application*

What is Method 3A?

Method 3A is a procedure for measuring oxygen (O<sub>2</sub>) and carbon dioxide (CO<sub>2</sub>) in sta-

tionary source emissions using a continuous instrumental analyzer. Quality assurance and quality control requirements are included to assure that you, the tester, collect data of known quality. You must document your adherence to these specific requirements for equipment, supplies, sample collection and analysis, calculations, and data analysis.

This method does not completely describe all equipment, supplies, and sampling and

analytical procedures you will need but refers to other methods for some of the details. Therefore, to obtain reliable results, you should also have a thorough knowledge of these additional test methods which are found in appendix A to this part:

- (a) Method 1—Sample and Velocity Transverses for Stationary Sources.
- (b) Method 3—Gas Analysis for the Determination of Molecular Weight.

(c) Method 4—Determination of Moisture Content in Stack Gases.

(d) Method 7E—Determination of Nitrogen Oxides Emissions from Stationary Sources (Instrumental Analyzer Procedure).

1.1 *Analytes. What does this method determine?* This method measures the concentration of oxygen and carbon dioxide.

Analyte	CAS No.	Sensitivity
Oxygen (O <sub>2</sub> ) .....	7782-44-7	Typically <2% of Calibration Span.
Carbon dioxide (CO <sub>2</sub> ) .....	124-38-9	Typically <2% of Calibration Span.

1.2 *Applicability. When is this method required?* The use of Method 3A may be required by specific New Source Performance Standards, Clean Air Marketing rules, State Implementation Plans and permits, where measurements of O<sub>2</sub> and CO<sub>2</sub> concentrations in stationary source emissions must be made, either to determine compliance with an applicable emission standard or to conduct performance testing of a continuous emission monitoring system (CEMS). Other regulations may also require the use of Method 3A.

1.3 *Data Quality Objectives. How good must my collected data be?* Refer to section 1.3 of Method 7E.

2.0 Summary of Method

In this method, you continuously or intermittently sample the effluent gas and convey the sample to an analyzer that measures the concentration of O<sub>2</sub> or CO<sub>2</sub>. You must meet the performance requirements of this method to validate your data.

3.0 Definitions

Refer to section 3.0 of Method 7E for the applicable definitions.

4.0 Interferences [Reserved]

5.0 Safety

Refer to section 5.0 of Method 7E.

6.0 Equipment and Supplies

Figure 7E-1 in Method 7E is a schematic diagram of an acceptable measurement system.

6.1 *What do I need for the measurement system?* The components of the measurement system are described (as applicable) in sections 6.1 and 6.2 of Method 7E, except that the analyzer described in section 6.2 of this method must be used instead of the analyzer described in Method 7E. You must follow the noted specifications in section 6.1 of Method 7E except that the requirements to use stainless steel, Teflon, or non-reactive glass filters do not apply. Also, a heated sample line

is not required to transport dry gases or for systems that measure the O<sub>2</sub> or CO<sub>2</sub> concentration on a dry basis, provided that the system is not also being used to concurrently measure SO<sub>2</sub> and/or NO<sub>x</sub>.

6.2 *What analyzer must I use?* You must use an analyzer that continuously measures O<sub>2</sub> or CO<sub>2</sub> in the gas stream and meets the specifications in section 13.0.

7.0 Reagents and Standards

7.1 *Calibration Gas. What calibration gases do I need?* Refer to Section 7.1 of Method 7E for the calibration gas requirements. Example calibration gas mixtures are listed below. Pre-cleaned or scrubbed air may be used for the O<sub>2</sub> high-calibration gas provided it does not contain other gases that interfere with the O<sub>2</sub> measurement.

- (a) CO<sub>2</sub> in Nitrogen (N<sub>2</sub>).
- (b) CO<sub>2</sub>/SO<sub>2</sub> gas mixture in N<sub>2</sub>.
- (c) O<sub>2</sub>/SO<sub>2</sub> gas mixture in N<sub>2</sub>.
- (d) O<sub>2</sub>/CO<sub>2</sub>/SO<sub>2</sub> gas mixture in N<sub>2</sub>.
- (e) CO<sub>2</sub>/NO<sub>x</sub> gas mixture in N<sub>2</sub>.
- (f) CO<sub>2</sub>/SO<sub>2</sub>/NO<sub>x</sub> gas mixture in N<sub>2</sub>.

The tests for analyzer calibration error and system bias require high-, mid-, and low-level gases.

7.2 *Interference Check. What reagents do I need for the interference check?* Potential interferences may vary among available analyzers. Table 7E-3 of Method 7E lists a number of gases that should be considered in conducting the interference test.

8.0 Sample Collection, Preservation, Storage, and Transport

8.1 *Sampling Site and Sampling Points.* You must follow the procedures of section 8.1 of Method 7E to determine the appropriate sampling points, unless you are using Method 3A only to determine the stack gas molecular weight and for no other purpose. In that case, you may use single-point integrated sampling as described in section 8.2.1 of Method 3. If the stratification test provisions in section 8.1.2 of Method 7E are used to reduce the number of required sampling points, the alternative acceptance criterion for 3-

point sampling will be  $\pm 0.5$  percent CO<sub>2</sub> or O<sub>2</sub>, and the alternative acceptance criterion for single-point sampling will be  $\pm 0.3$  percent CO<sub>2</sub> or O<sub>2</sub>. In that case, you may use single-point integrated sampling as described in section 8.2.1 of Method 3.

**8.2 Initial Measurement System Performance Tests.** You must follow the procedures in section 8.2 of Method 7E. If a dilution-type measurement system is used, the special considerations in section 8.3 of Method 7E apply.

**8.3 Interference Check.** The O<sub>2</sub> or CO<sub>2</sub> analyzer must be documented to show that interference effects to not exceed 2.5 percent of the calibration span. The interference test in section 8.2.7 of Method 7E is a procedure that may be used to show this. The effects of all potential interferences at the concentrations encountered during testing must be addressed and documented. This testing and documentation may be done by the instrument manufacturer.

**8.4 Sample Collection.** You must follow the procedures in section 8.4 of Method 7E.

**8.5 Post-Run System Bias Check and Drift Assessment.** You must follow the procedures in section 8.5 of Method 7E.

**9.0 Quality Control**

Follow quality control procedures in section 9.0 of Method 7E.

**10.0 Calibration and Standardization**

Follow the procedures for calibration and standardization in section 10.0 of Method 7E.

**11.0 Analytical Procedures**

Because sample collection and analysis are performed together (see section 8), additional discussion of the analytical procedure is not necessary.

**12.0 Calculations and Data Analysis**

You must follow the applicable procedures for calculations and data analysis in section

Analyte	CAS No.	Sensitivity
Oxygen (O <sub>2</sub> )	7782-44-7	2,000 ppmv.
Carbon Dioxide (CO <sub>2</sub> )	124-38-9	2,000 ppmv.
Carbon Monoxide (CO)	630-08-0	N/A.

**1.2 Applicability.** This method is applicable for the determination of O<sub>2</sub>, CO<sub>2</sub>, and CO concentrations in the effluent from fossil-fuel combustion processes for use in excess air or emission rate correction factor calculations. Where compounds other than CO<sub>2</sub>, O<sub>2</sub>, CO, and nitrogen (N<sub>2</sub>) are present in concentrations sufficient to affect the results, the calculation procedures presented in this method must be modified, subject to the approval of the Administrator.

12.0 of Method 7E, substituting percent O<sub>2</sub> and percent CO<sub>2</sub> for ppmv of NO<sub>x</sub> as appropriate.

**13.0 Method Performance**

The specifications for the applicable performance checks are the same as in section 13.0 of Method 7E except for the alternative specifications for system bias, drift, and calibration error. In these alternative specifications, replace the term "0.5 ppmv" with the term "0.5 percent O<sub>2</sub>" or "0.5 percent CO<sub>2</sub>" (as applicable).

**14.0 Pollution Prevention [Reserved]**

**15.0 Waste Management [Reserved]**

**16.0 Alternative Procedures [Reserved]**

**17.0 References**

- "EPA Traceability Protocol for Assay and Certification of Gaseous Calibration Standards" September 1997 as amended, EPA-600/R-97/121.

**18.0 Tables, Diagrams, Flowcharts, and Validation Data**

Refer to section 18.0 of Method 7E.

**METHOD 3B—GAS ANALYSIS FOR THE DETERMINATION OF EMISSION RATE CORRECTION FACTOR OR EXCESS AIR**

**NOTE:** This method does not include all of the specifications (e.g., equipment and supplies) and procedures (e.g., sampling) essential to its performance. Some material is incorporated by reference from other methods in this part. Therefore, to obtain reliable results, persons using this method should have a thorough knowledge of at least the following additional test methods: Method 1 and 3.

**1.0 Scope and Application**

**1.1 Analytes.**

**1.3 Other methods,** as well as modifications to the procedure described herein, are also applicable for all of the above determinations. Examples of specific methods and modifications include: (1) A multi-point sampling method using an Orsat analyzer to analyze individual grab samples obtained at each point, and (2) a method using CO<sub>2</sub> or O<sub>2</sub> and stoichiometric calculations to determine excess air. These methods and modifications may be used, but are subject to the approval of the Administrator.

1.4 Data Quality Objectives. Adherence to the requirements of this method will enhance the quality of the data obtained from air pollutant sampling methods.

#### 2.0 Summary of Method

2.1 A gas sample is extracted from a stack by one of the following methods: (1) Single-point, grab sampling; (2) single-point, integrated sampling; or (3) multi-point, integrated sampling. The gas sample is analyzed for percent CO<sub>2</sub>, percent O<sub>2</sub>, and, if necessary, percent CO using an Orsat combustion gas analyzer.

#### 3.0 Definitions [Reserved]

#### 4.0 Interferences

4.1 Several compounds can interfere, to varying degrees, with the results of Orsat analyses. Compounds that interfere with CO<sub>2</sub> concentration measurement include acid gases (*e.g.*, sulfur dioxide, hydrogen chloride); compounds that interfere with O<sub>2</sub> concentration measurement include unsaturated hydrocarbons (*e.g.*, acetone, acetylene), nitrous oxide, and ammonia. Ammonia reacts chemically with the O<sub>2</sub> absorbing solution, and when present in the effluent gas stream must be removed before analysis.

#### 5.0 Safety

5.1 Disclaimer. This method may involve hazardous materials, operations, and equipment. This test method may not address all of the safety problems associated with its use. It is the responsibility of the user of this test method to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to performing this test method.

5.2 Corrosive Reagents. A typical Orsat analyzer requires four reagents: a gas-confining solution, CO<sub>2</sub> absorbent, O<sub>2</sub> absorbent, and CO absorbent. These reagents may contain potassium hydroxide, sodium hydroxide, cuprous chloride, cuprous sulfate, alkaline pyrogallol acid, and/or chromous chloride. Follow manufacturer's operating instructions and observe all warning labels for reagent use.

#### 6.0 Equipment and Supplies

NOTE: As an alternative to the sampling apparatus and systems described herein, other sampling systems (*e.g.*, liquid displacement) may be used, provided such systems are capable of obtaining a representative sample and maintaining a constant sampling rate, and are, otherwise, capable of yielding acceptable results. Use of such systems is subject to the approval of the Administrator.

6.1 Grab Sampling and Integrated Sampling. Same as in sections 6.1 and 6.2, respectively for Method 3.

6.2 Analysis. An Orsat analyzer only. For low CO<sub>2</sub> (less than 4.0 percent) or high O<sub>2</sub> (greater than 15.0 percent) concentrations, the measuring burette of the Orsat must have at least 0.1 percent subdivisions. For Orsat maintenance and operation procedures, follow the instructions recommended by the manufacturer, unless otherwise specified herein.

#### 7.0 Reagents and Standards

7.1 Reagents. Same as in Method 3, section 7.1.

7.2 Standards. Same as in Method 3, section 7.2.

#### 8.0 Sample Collection, Preservation, Storage, and Transport

NOTE: Each of the three procedures below shall be used only when specified in an applicable subpart of the standards. The use of these procedures for other purposes must have specific prior approval of the Administrator. A Fyrite-type combustion gas analyzer is not acceptable for excess air or emission rate correction factor determinations, unless approved by the Administrator. If both percent CO<sub>2</sub> and percent O<sub>2</sub> are measured, the analytical results of any of the three procedures given below may also be used for calculating the dry molecular weight (see Method 3).

8.1 Single-Point, Grab Sampling and Analytical Procedure.

8.1.1 The sampling point in the duct shall either be at the centroid of the cross section or at a point no closer to the walls than 1.0 m (3.3 ft), unless otherwise specified by the Administrator.

8.1.2 Set up the equipment as shown in Figure 3-1 of Method 3, making sure all connections ahead of the analyzer are tight. Leak-check the Orsat analyzer according to the procedure described in section 11.5 of Method 3. This leak-check is mandatory.

8.1.3 Place the probe in the stack, with the tip of the probe positioned at the sampling point; purge the sampling line long enough to allow at least five exchanges. Draw a sample into the analyzer. For emission rate correction factor determinations, immediately analyze the sample for percent CO<sub>2</sub> or percent O<sub>2</sub>, as outlined in section 11.2. For excess air determination, immediately analyze the sample for percent CO<sub>2</sub>, O<sub>2</sub>, and CO, as outlined in section 11.2, and calculate excess air as outlined in section 12.2.

8.1.4 After the analysis is completed, leak-check (mandatory) the Orsat analyzer once again, as described in section 11.5 of Method 3. For the results of the analysis to be valid, the Orsat analyzer must pass this leak-test before and after the analysis.

8.2 Single-Point, Integrated Sampling and Analytical Procedure.

8.2.1 The sampling point in the duct shall be located as specified in section 8.1.1.

8.2.2 Leak-check (mandatory) the flexible bag as in section 6.2.6 of Method 3. Set up the equipment as shown in Figure 3-2 of Method 3. Just before sampling, leak-check (mandatory) the train by placing a vacuum gauge at the condenser inlet, pulling a vacuum of at least 250 mm Hg (10 in. Hg), plugging the outlet at the quick disconnect, and then turning off the pump. The vacuum should remain stable for at least 0.5 minute. Evacuate the flexible bag. Connect the probe, and place it in the stack, with the tip of the probe positioned at the sampling point; purge the sampling line. Next, connect the bag, and make sure that all connections are tight.

8.2.3 Sample at a constant rate, or as specified by the Administrator. The sampling run must be simultaneous with, and for the same total length of time as, the pollutant emission rate determination. Collect at least 28 liters (1.0 ft<sup>3</sup>) of sample gas. Smaller volumes may be collected, subject to approval of the Administrator.

8.2.4 Obtain one integrated flue gas sample during each pollutant emission rate determination. For emission rate correction factor determination, analyze the sample within 4 hours after it is taken for percent CO<sub>2</sub> or percent O<sub>2</sub> (as outlined in section 11.2).

8.3 Multi-Point, Integrated Sampling and Analytical Procedure.

8.3.1 Unless otherwise specified in an applicable regulation, or by the Administrator, a minimum of eight traverse points shall be used for circular stacks having diameters less than 0.61 m (24 in.), a minimum of nine shall be used for rectangular stacks having equivalent diameters less than 0.61 m (24 in.), and a minimum of 12 traverse points shall be used for all other cases. The traverse points shall be located according to Method 1.

8.3.2 Follow the procedures outlined in sections 8.2.2 through 8.2.4, except for the following: Traverse all sampling points, and sample at each point for an equal length of time. Record sampling data as shown in Figure 3-3 of Method 3.

#### 9.0 Quality Control

9.1 Data Validation Using Fuel Factor. Although in most instances, only CO<sub>2</sub> or O<sub>2</sub> measurement is required, it is recommended that both CO<sub>2</sub> and O<sub>2</sub> be measured to provide a check on the quality of the data. The data validation procedure of section 12.3 is suggested.

NOTE: Since this method for validating the CO<sub>2</sub> and O<sub>2</sub> analyses is based on combustion of organic and fossil fuels and dilution of the gas stream with air, this method does not apply to sources that (1) remove CO<sub>2</sub> or O<sub>2</sub> through processes other than combustion, (2) add O<sub>2</sub> (e.g., oxygen enrichment) and N<sub>2</sub> in proportions different from that of air, (3) add

CO<sub>2</sub> (e.g., cement or lime kilns), or (4) have no fuel factor, F<sub>O</sub>, values obtainable (e.g., extremely variable waste mixtures). This method validates the measured proportions of CO<sub>2</sub> and O<sub>2</sub> for fuel type, but the method does not detect sample dilution resulting from leaks during or after sample collection. The method is applicable for samples collected downstream of most lime or limestone flue-gas desulfurization units as the CO<sub>2</sub> added or removed from the gas stream is not significant in relation to the total CO<sub>2</sub> concentration. The CO<sub>2</sub> concentrations from other types of scrubbers using only water or basic slurry can be significantly affected and would render the fuel factor check minimally useful.

#### 10.0 Calibration and Standardization

10.1 Analyzer. The analyzer and analyzer operator technique should be audited periodically as follows: take a sample from a manifold containing a known mixture of CO<sub>2</sub> and O<sub>2</sub>, and analyze according to the procedure in section 11.3. Repeat this procedure until the measured concentration of three consecutive samples agrees with the stated value  $\pm 0.5$  percent. If necessary, take corrective action, as specified in the analyzer users manual.

10.2 Rotameter. The rotameter need not be calibrated, but should be cleaned and maintained according to the manufacturer's instruction.

#### 11.0 Analytical Procedure

11.1 Maintenance. The Orsat analyzer should be maintained according to the manufacturers specifications.

11.2 Grab Sample Analysis. To ensure complete absorption of the CO<sub>2</sub>, O<sub>2</sub>, or if applicable, CO, make repeated passes through each absorbing solution until two consecutive readings are the same. Several passes (three or four) should be made between readings. (If constant readings cannot be obtained after three consecutive readings, replace the absorbing solution.) Although in most cases, only CO<sub>2</sub> or O<sub>2</sub> concentration is required, it is recommended that both CO<sub>2</sub> and O<sub>2</sub> be measured, and that the procedure in section 12.3 be used to validate the analytical data.

NOTE: Since this single-point, grab sampling and analytical procedure is normally conducted in conjunction with a single-point, grab sampling and analytical procedure for a pollutant, only one analysis is ordinarily conducted. Therefore, great care must be taken to obtain a valid sample and analysis.

11.3 Integrated Sample Analysis. The Orsat analyzer must be leak-checked (see section 11.5 of Method 3) before the analysis. If excess air is desired, proceed as follows: (1) within 4 hours after the sample is taken, analyze it (as in sections 11.3.1 through

11.3.3) for percent CO<sub>2</sub>, O<sub>2</sub>, and CO; (2) determine the percentage of the gas that is N<sub>2</sub> by subtracting the sum of the percent CO<sub>2</sub>, percent O<sub>2</sub>, and percent CO from 100 percent; and (3) calculate percent excess air, as outlined in section 12.2.

11.3.1 To ensure complete absorption of the CO<sub>2</sub>, O<sub>2</sub>, or if applicable, CO, follow the procedure described in section 11.2.

NOTE: Although in most instances only CO<sub>2</sub> or O<sub>2</sub> is required, it is recommended that both CO<sub>2</sub> and O<sub>2</sub> be measured, and that the procedures in section 12.3 be used to validate the analytical data.

11.3.2 Repeat the analysis until the following criteria are met:

11.3.2.1 For percent CO<sub>2</sub>, repeat the analytical procedure until the results of any three analyses differ by no more than (a) 0.3 percent by volume when CO<sub>2</sub> is greater than 4.0 percent or (b) 0.2 percent by volume when CO<sub>2</sub> is less than or equal to 4.0 percent. Average three acceptable values of percent CO<sub>2</sub>, and report the results to the nearest 0.2 percent.

11.3.2.2 For percent O<sub>2</sub>, repeat the analytical procedure until the results of any three analyses differ by no more than (a) 0.3 percent by volume when O<sub>2</sub> is less than 15.0 percent or (b) 0.2 percent by volume when O<sub>2</sub> is greater than or equal to 15.0 percent. Average the three acceptable values of percent

O<sub>2</sub>, and report the results to the nearest 0.1 percent.

11.3.2.3 For percent CO, repeat the analytical procedure until the results of any three analyses differ by no more than 0.3 percent. Average the three acceptable values of percent CO, and report the results to the nearest 0.1 percent.

11.3.3 After the analysis is completed, leak-check (mandatory) the Orsat analyzer once again, as described in section 11.5 of Method 3. For the results of the analysis to be valid, the Orsat analyzer must pass this leak-test before and after the analysis.

11.4 Standardization. A periodic check of the reagents and of operator technique should be conducted at least once every three series of test runs as indicated in section 10.1.

12.0 Calculations and Data Analysis

12.1 Nomenclature. Same as section 12.1 of Method 3 with the addition of the following:  
%EA = Percent excess air.  
0.264 = Ratio of O<sub>2</sub> to N<sub>2</sub> in air, v/v.

12.2 Percent Excess Air. Determine the percentage of the gas that is N<sub>2</sub> by subtracting the sum of the percent CO<sub>2</sub>, percent CO, and percent O<sub>2</sub> from 100 percent. Calculate the percent excess air (if applicable) by substituting the appropriate values of percent O<sub>2</sub>, CO, and N<sub>2</sub> into Equation 3B-1.

$$\%EA = \frac{\%O_2 - 0.5 \%CO}{0.264 \%N_2 - (\%O_2 - 0.5 \%CO)} \times 100 \quad \text{Eq. 3B-1}$$

NOTE: The equation above assumes that ambient air is used as the source of O<sub>2</sub> and that the fuel does not contain appreciable amounts of N<sub>2</sub> (as do coke oven or blast furnace gases). For those cases when appreciable amounts of N<sub>2</sub> are present (coal, oil, and natural gas do not contain appreciable amounts of N<sub>2</sub>) or when oxygen enrichment is used, alternative methods, subject to approval of the Administrator, are required.

12.3 Data Validation When Both CO<sub>2</sub> and O<sub>2</sub> Are Measured.

12.3.1 Fuel Factor, F<sub>o</sub>. Calculate the fuel factor (if applicable) using Equation 3B-2:

$$F_o = \frac{20.9 - \%O_2}{\%CO_2} \quad \text{Eq. 3B-2}$$

Where:

%O<sub>2</sub> = Percent O<sub>2</sub> by volume, dry basis.  
%CO<sub>2</sub> = Percent CO<sub>2</sub> by volume, dry basis.  
20.9 = Percent O<sub>2</sub> by volume in ambient air.

If CO is present in quantities measurable by this method, adjust the O<sub>2</sub> and CO<sub>2</sub> values

using Equations 3B-3 and 3B-4 before performing the calculation for F<sub>o</sub>:

$$\%CO_2(\text{adj}) = \%CO_2 + \%CO \quad \text{Eq. 3B-3}$$

$$\%O_2(\text{adj}) = \%O_2 - 0.5 \%CO \quad \text{Eq. 3B-4}$$

Where:

%CO = Percent CO by volume, dry basis.

12.3.2 Compare the calculated F<sub>o</sub> factor with the expected F<sub>o</sub> values. Table 3B-1 in section 17.0 may be used in establishing acceptable ranges for the expected F<sub>o</sub>, if the fuel being burned is known. When fuels are burned in combinations, calculate the combined fuel F<sub>a</sub> and F<sub>c</sub> factors (as defined in Method 19, section 12.2) according to the procedure in Method 19, sections 12.2 and 12.3. Then calculate the F<sub>o</sub> factor according to Equation 3B-5.

$$F_o = \frac{0.209 F_d}{F_c} \quad \text{Eq. 3B-5}$$



12.3.3 Calculated  $F_o$  values, beyond the acceptable ranges shown in this table, should be investigated before accepting the test results. For example, the strength of the solutions in the gas analyzer and the analyzing technique should be checked by sampling and analyzing a known concentration, such as air; the fuel factor should be reviewed and verified. An acceptability range of  $\pm 12$  percent is appropriate for the  $F_o$  factor of mixed fuels with variable fuel ratios. The level of the emission rate relative to the compliance level should be considered in determining if a retest is appropriate; i.e., if the measured emissions are much lower or much greater than the compliance limit, repetition of the test would not significantly change the compliance status of the source and would be unnecessarily time consuming and costly.

13.0 Method Performance [Reserved]

14.0 Pollution Prevention [Reserved]

15.0 Waste Management [Reserved]

16.0 References

Same as Method 3, section 16.0.

17.0 Tables, Diagrams, Flowcharts, and Validation Data

TABLE 3B-1— $F_o$  FACTORS FOR SELECTED FUELS

Fuel type	$F_o$ range
Coal:	
Anthracite and lignite .....	1.016-1.130
Bituminous .....	1.083-1.230
Oil:	
Distillate .....	1.260-1.413
Residual .....	1.210-1.370
Gas:	
Natural .....	1.600-1.836
Propane .....	1.434-1.586
Butane .....	1.405-1.553
Wood .....	1.000-1.120
Wood bark .....	1.003-1.130

METHOD 3C—DETERMINATION OF CARBON DIOXIDE, METHANE, NITROGEN, AND OXYGEN FROM STATIONARY SOURCES

1. Applicability and Principle

1.1 Applicability. This method applies to the analysis of carbon dioxide ( $CO_2$ ), methane ( $CH_4$ ), nitrogen ( $N_2$ ), and oxygen ( $O_2$ ) in samples from municipal solid waste landfills and other sources when specified in an applicable subpart.

1.2 Principle. A portion of the sample is injected into a gas chromatograph (GC) and the  $CO_2$ ,  $CH_4$ ,  $N_2$ , and  $O_2$  concentrations are determined by using a thermal conductivity detector (TCD) and integrator.

2. Range and Sensitivity

2.1 Range. The range of this method depends upon the concentration of samples. The analytical range of TCD's is generally between approximately 10 ppmv and the upper percent range.

2.2 Sensitivity. The sensitivity limit for a compound is defined as the minimum detectable concentration of that compound, or the concentration that produces a signal-to-noise ratio of three to one. For  $CO_2$ ,  $CH_4$ ,  $N_2$ , and  $O_2$ , the sensitivity limit is in the low ppmv range.

3. Interferences

Since the TCD exhibits universal response and detects all gas components except the carrier, interferences may occur. Choosing the appropriate GC or shifting the retention times by changing the column flow rate may help to eliminate resolution interferences.

To assure consistent detector response, helium is used to prepare calibration gases. Frequent exposure to samples or carrier gas containing oxygen may gradually destroy filaments.

4. Apparatus

4.1 Gas Chromatograph. GC having at least the following components:

4.1.1 Separation Column. Appropriate column(s) to resolve  $CO_2$ ,  $CH_4$ ,  $N_2$ ,  $O_2$ , and other gas components that may be present in the sample.

4.1.2 Sample Loop. Teflon or stainless steel tubing of the appropriate diameter.

NOTE: Mention of trade names or specific products does not constitute endorsement or recommendation by the U. S. Environmental Protection Agency.

4.1.3 Conditioning System. To maintain the column and sample loop at constant temperature.

4.1.4 Thermal Conductivity Detector.

4.2 Recorder. Recorder with linear strip chart. Electronic integrator (optional) is recommended.

4.3 Teflon Tubing. Diameter and length determined by connection requirements of cylinder regulators and the GC.

4.4 Regulators. To control gas cylinder pressures and flow rates.

4.5 Adsorption Tubes. Applicable traps to remove any  $O_2$  from the carrier gas.

5. Reagents

5.1 Calibration and Linearity Gases. Standard cylinder gas mixtures for each compound of interest with at least three concentration levels spanning the range of suspected sample concentrations. The calibration gases shall be prepared in helium.

5.2 Carrier Gas. Helium, high-purity.

## 6. Analysis

6.1 Sample Collection. Use the sample collection procedures described in Methods 3 or 25C to collect a sample of landfill gas (LFG).

6.2 Preparation of GC. Before putting the GC analyzer into routine operation, optimize the operational conditions according to the manufacturer's specifications to provide good resolution and minimum analysis time. Establish the appropriate carrier gas flow and set the detector sample and reference cell flow rates at exactly the same levels. Adjust the column and detector temperatures to the recommended levels. Allow sufficient time for temperature stabilization. This may typically require 1 hour for each change in temperature.

6.3 Analyzer Linearity Check and Calibration. Perform this test before sample analysis.

6.3.1 Using the gas mixtures in section 5.1, verify the detector linearity over the range of suspected sample concentrations with at least three concentrations per compound of interest. This initial check may also serve as the initial instrument calibration.

6.3.2 You may extend the use of the analyzer calibration by performing a single-point calibration verification. Calibration verifications shall be performed by triplicate injections of a single-point standard gas. The concentration of the single-point calibration must either be at the midpoint of the calibration curve or at approximately the source emission concentration measured during operation of the analyzer.

6.3.3 Triplicate injections must agree within 5 percent of their mean, and the average calibration verification point must agree within 10 percent of the initial calibration response factor. If these calibration verification criteria are not met, the initial calibration described in section 6.3.1, using at least three concentrations, must be repeated before analysis of samples can continue.

6.3.4 For each instrument calibration, record the carrier and detector flow rates, detector filament and block temperatures, attenuation factor, injection time, chart speed, sample loop volume, and component concentrations.

6.3.5 Plot a linear regression of the standard concentrations versus area values to obtain the response factor of each compound. Alternatively, response factors of uncorrected component concentrations (wet basis) may be generated using instrumental integration.

NOTE: Peak height may be used instead of peak area throughout this method.

6.4 Sample Analysis. Purge the sample loop with sample, and allow to come to atmospheric pressure before each injection. Analyze each sample in duplicate, and calculate

the average sample area (A). The results are acceptable when the peak areas for two consecutive injections agree within 5 percent of their average. If they do not agree, run additional samples until consistent area data are obtained. Determine the tank sample concentrations according to section 7.2.

## 7. Calculations

Carry out calculations retaining at least one extra decimal figure beyond that of the acquired data. Round off results only after the final calculation.

## 7.1 Nomenclature.

$B_w$  = Moisture content in the sample, fraction.

$C_{N_2}$  = Measured  $N_2$  concentration (by Method 3C), fraction.

$C_{N_2C_{cor}}$  = Measured  $N_2$  concentration corrected only for dilution, fraction.

$C_i$  = Calculated NMOC concentration, ppmv C equivalent.

$C_m$  = Measured NMOC concentration, ppmv C equivalent.

$P_b$  = Barometric pressure, mm Hg.

$P_i$  = Gas sample tank pressure after sampling, but before pressurizing, mm Hg absolute.

$P_{if}$  = Final gas sample tank pressure after pressurizing, mm Hg absolute.

$P_{ii}$  = Gas sample tank pressure after evacuation, mm Hg absolute.

$P_w$  = Vapor pressure of  $H_2O$  (from Table 25C-1), mm Hg.

$r$  = Total number of analyzer injections of sample tank during analysis (where  $j$  = injection number, 1 . . .  $r$ ).

$R$  = Mean calibration response factor for specific sample component, area/ppm.

$T_i$  = Sample tank temperature at completion of sampling, °K.

$T_{ii}$  = Sample tank temperature before sampling, °K.

$T_{if}$  = Sample tank temperature after pressurizing, °K.

7.2 Concentration of Sample Components. Calculate C for each compound using Equations 3C-1 and 3C-2. Use the temperature and barometric pressure at the sampling site to calculate  $B_w$ . If the sample was diluted with helium using the procedures in Method 25C, use Equation 3C-3 to calculate the concentration.

$$B_w = \frac{P_w}{P_{\text{bar}}} \quad 3C-1$$

$$C = \frac{A}{R(1-B_w)} \quad 3C-2$$

$$C = \frac{\frac{P_{tf}}{T_{tf}}}{\frac{P_t - P_{ti}}{T_t - T_{ti}}} \cdot \frac{A}{R(1-B_w)} \quad 3C-3$$

$$C_{N_2 \text{ Corr}} = \frac{\frac{P_{tf}}{T_{tf}}}{\frac{P_t - P_{ti}}{T_t - T_{ti}}} (C_{N_2}) \quad \text{Eq. 3C-4}$$

7.3 Measured  $N_2$  Concentration Correction. Calculate the reported  $N_2$  correction for Method 25-C using Eq. 3C-4. If oxygen is determined in place of  $N_2$ , substitute the oxygen concentration for the nitrogen concentration in the equation.

### 8. Bibliography

1. McNair, H.M., and E.J. Bonnelly, Basic Gas Chromatography. Consolidated Printers, Berkeley, CA. 1969.

[36 FR 24877, Dec. 23, 1971]

EDITORIAL NOTE: For FEDERAL REGISTER citations affecting appendix A-2 to part 60, see the List of CFR sections Affected, which appears in the Finding Aids section of the printed volume and at [www.fdsys.gov](http://www.fdsys.gov).

#### APPENDIX A-3 TO PART 60—TEST METHODS 4 THROUGH 5I

- Method 4—Determination of moisture content in stack gases
- Method 5—Determination of particulate matter emissions from stationary sources
- Method 5A—Determination of particulate matter emissions from the asphalt processing and asphalt roofing industry
- Method 5B—Determination of nonsulfuric acid particulate matter emissions from stationary sources
- Method 5C [Reserved]
- Method 5D—Determination of particulate matter emissions from positive pressure fabric filters
- Method 5E—Determination of particulate matter emissions from the wool fiber-glass insulation manufacturing industry

Method 5F—Determination of nonsulfate particulate matter emissions from stationary sources

Method 5G—Determination of particulate matter emissions from wood heaters (dilution tunnel sampling location)

Method 5H—Determination of particulate emissions from wood heaters from a stack location

Method 5I—Determination of Low Level Particulate Matter Emissions From Stationary Sources

The test methods in this appendix are referred to in §60.8 (Performance Tests) and §60.11 (Compliance With Standards and Maintenance Requirements) of 40 CFR part 60, subpart A (General Provisions). Specific uses of these test methods are described in the standards of performance contained in the subparts, beginning with Subpart D.

Within each standard of performance, a section title "Test Methods and Procedures" is provided to: (1) identify the test methods to be used as reference methods to the facility subject to the respective standard and (2) identify any special instructions or conditions to be followed when applying a method to the respective facility. Such instructions (for example, establish sampling rates, volumes, or temperatures) are to be used either in addition to, or as a substitute for procedures in a test method. Similarly, for sources subject to emission monitoring requirements, specific instructions pertaining to any use of a test method as a reference