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Method 2F - Determination of Stack Gas Velocity And Volumetric Flow Rate With Three-Dimensional Probes

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 has been incorporated from other methods in this part. Therefore, to obtain reliable results, those using this method should have a thorough knowledge of at least the following additional test methods: Methods 1, 2, 3 or 3A, and 4.

1.0 Scope and Application

1.1 This method is applicable for the determination of yaw angle, pitch angle, axial velocity and the volumetric flow rate of a gas stream in a stack or duct using a three-dimensional (3-D) probe. This method may be used only when the average stack or duct gas velocity is greater than or equal to 20 ft/sec. When the above condition cannot be met, alternative procedures, approved by the Administrator, U.S. Environmental Protection Agency, shall be used to make accurate flow rate determinations.

2.0 Summary of Method

2.1 A 3-D probe is used to determine the velocity pressure and the yaw and pitch angles of the flow velocity vector in a stack or duct. The method determines the yaw angle directly by rotating the probe to null the pressure across a pair of symmetrically placed ports on the probe head. The pitch angle is calculated using probe-specific calibration curves. From these values and a determination of the stack gas density, the average axial velocity of the stack gas is calculated. The average gas volumetric flow rate in the stack or duct is then determined from the average axial velocity.

3.0 Definitions

3.1 *Angle-measuring Device Rotational Offset* (R_{ADO}). The rotational position of an angle-measuring device relative to the reference scribe line, as determined during the pre-test rotational position check described in section 8.3.

3.2 *Axial Velocity*. The velocity vector parallel to the axis of the stack or duct that accounts for the yaw and pitch angle components of gas flow. The term “axial” is used herein to indicate that the velocity and volumetric flow rate results account for the measured yaw and pitch components of flow at each measurement point.

3.3 *Calibration Pitot Tube*. The standard (Prandtl type) pitot tube used as a reference when calibrating a 3-D probe under this method.

3.4 *Field Test*. A set of measurements conducted at a specific unit or exhaust stack/duct to satisfy the applicable regulation (e.g., a three-run boiler performance test, a single-or multiple-load nine-run relative accuracy test).

3.5 *Full Scale of Pressure-measuring Device*. Full scale refers to the upper limit of the measurement range displayed by the device. For bi-directional pressure gauges, full scale includes the entire pressure range from the lowest negative value to the highest positive value on the pressure scale.

3.6 *Main probe*. Refers to the probe head and that section of probe sheath directly attached to the probe head. The main probe sheath is distinguished from probe extensions, which are sections of sheath added onto the main probe to extend its reach.

3.7 “*May*,” “*Must*,” “*Shall*,” “*Should*,” and the imperative form of verbs.

3.7.1 “*May*” is used to indicate that a provision of this method is optional.

3.7.2 “*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.

3.7.3 “*Should*” is used to indicate that a provision of this method is not mandatory, but is highly recommended as good practice.

3.8 *Method 1*. Refers to 40 CFR part 60, appendix A, “Method 1—Sample and velocity traverses for stationary sources.”

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

3.11 *Nominal Velocity*. Refers to a wind tunnel velocity setting that approximates the actual wind tunnel velocity to within ± 1.5 m/sec (± 5 ft/sec).

3.12 *Pitch Angle*. The angle between the axis of the stack or duct and the pitch component of flow, i.e., the component of the total velocity vector in a plane defined by the traverse line and the axis of the stack or duct. (Figure 2F-1 illustrates the “pitch plane.”) From the standpoint of a tester facing a test port in a vertical stack, the pitch component of flow is the vector of flow moving from the center of the stack toward or away from that test port. The pitch angle is the angle described by this pitch component of flow and the vertical axis of the stack.

3.13 *Readability*. For the purposes of this method, readability for an analog measurement device is one half of the smallest scale division. For a digital measurement device, it is the number of decimals displayed by the device.

3.14 *Reference Scribe Line*. A line permanently inscribed on the main probe sheath (in accordance with section 6.1.6.1) to serve as a reference mark for determining yaw angles.

3.15 *Reference Scribe Line Rotational Offset* (R_{SLO}). The rotational position of a probe's reference scribe line relative to the probe's yaw-null position, as determined during the yaw angle calibration described in section 10.5.

3.16 *Response Time*. The time required for the measurement system to fully respond to a change from zero differential pressure and ambient temperature to the stable stack or duct pressure and temperature readings at a traverse point.

3.17 *Tested Probe*. A 3-D probe that is being calibrated.

3.18 *Three-dimensional (3-D) Probe*. A directional probe used to determine the velocity pressure and yaw and pitch angles in a flowing gas stream.

3.19 *Traverse Line*. A diameter or axis extending across a stack or duct on which measurements of differential pressure and flow angles are made.

3.20 *Wind Tunnel Calibration Location*. A point, line, area, or volume within the wind tunnel test section at, along, or within which probes are calibrated. At a particular wind tunnel velocity setting, the average velocity pressures at specified points at, along, or within the calibration location shall vary by no more than 2 percent or 0.3 mm H₂O (0.01 in. H₂O), whichever is less restrictive, from the average velocity pressure at the calibration pitot tube location. Air flow at this location shall be axial, i.e., yaw and pitch angles within $\pm 3^\circ$. Compliance with these flow criteria shall be demonstrated by performing the procedures prescribed in sections 10.1.1 and 10.1.2. For circular tunnels, no part of the calibration location may be closer to the tunnel wall than 10.2 cm (4 in.) or 25 percent of the tunnel diameter, whichever is farther from the wall. For elliptical or rectangular tunnels, no part of the calibration location may be closer to the tunnel wall than 10.2 cm (4 in.) or 25 percent of the applicable cross-sectional axis, whichever is farther from the wall.

3.21 *Wind Tunnel with Documented Axial Flow*. A wind tunnel facility documented as meeting the provisions of sections 10.1.1 (velocity pressure cross-check) and 10.1.2 (axial flow verification) using the procedures described in these sections or alternative procedures determined to be technically equivalent.

3.22 *Yaw Angle*. The angle between the axis of the stack or duct and the yaw component of flow, i.e., the component of the total velocity vector in a plane perpendicular to the traverse line at a particular traverse point. (Figure 2F-1 illustrates the "yaw plane.") From the standpoint of a tester facing a test port in a vertical stack, the yaw component of flow is the vector of flow moving to the left or right from the center of the stack as viewed by the tester. (This is sometimes referred to as "vortex flow," i.e., flow around the centerline of a stack or duct.) The yaw angle is the angle described by this yaw component of flow and the vertical axis of the stack. The algebraic sign convention is illustrated in Figure 2F-2.

3.23 *Yaw Nulling.* A procedure in which a probe is rotated about its axis in a stack or duct until a zero differential pressure reading (“yaw null”) is obtained. When a 3–D probe is yaw-nulled, its impact pressure port (P_1) faces directly into the direction of flow in the stack or duct and the differential pressure between pressure ports P_2 and P_3 is zero.

4.0 *Interferences[Reserved]*

5.0 *Safety*

5.1 This test method may involve hazardous operations and the use of hazardous materials or equipment. This method does not purport to address all of the safety problems associated with its use. It is the responsibility of the user to establish and implement appropriate safety and health practices and to determine the applicability of regulatory limitations before using this test method.

6.0 *Equipment and Supplies*

6.1 *Three-dimensional Probes.* The 3–D probes as specified in subsections 6.1.1 through 6.1.3 below qualify for use based on comprehensive wind tunnel and field studies involving both inter- and intra-probe comparisons by multiple test teams. Other types of probes shall not be used unless approved by the Administrator. Each 3–D probe shall have a unique identification number or code permanently marked on the main probe sheath. The minimum recommended diameter of the sensing head of any probe used under this method is 2.5 cm (1 in.). Each probe shall be calibrated prior to use according to the procedures in section 10. Manufacturer-supplied calibration data shall be used as example information only, except when the manufacturer calibrates the 3–D probe as specified in section 10 and provides complete documentation.

6.1.1 *Five-hole prism-shaped probe.* This type of probe consists of five pressure taps in the flat facets of a prism-shaped sensing head. The pressure taps are numbered 1 through 5, with the pressures measured at each hole referred to as P_1 , P_2 , P_3 , P_4 , and P_5 , respectively. Figure 2F–3 is an illustration of the placement of pressure taps on a commonly available five-hole prism-shaped probe, the 2.5-cm (1-in.) DAT probe. (Note: Mention of trade names or specific products does not constitute endorsement by the U.S. Environmental Protection Agency.) The numbering arrangement for the prism-shaped sensing head presented in Figure 2F–3 shall be followed for correct operation of the probe. A brief description of the probe measurements involved is as follows: the differential pressure P_2 – P_3 is used to yaw null the probe and determine the yaw angle; the differential pressure P_4 – P_5 is a function of pitch angle; and the differential pressure P_1 – P_2 is a function of total velocity.

6.1.2 *Five-hole spherical probe.* This type of probe consists of five pressure taps in a spherical sensing head. As with the prism-shaped probe, the pressure taps are numbered 1 through 5, with the pressures measured at each hole referred to as P_1 , P_2 , P_3 , P_4 , and P_5 , respectively. However, the P_4 and P_5 pressure taps are in the reverse location from their respective positions on the prism-shaped probe head. The differential pressure P_2 – P_3 is used to yaw null the probe and determine the yaw angle; the differential pressure P_4 – P_5 is a function of pitch angle; and the differential pressure P_1 – P_2 is a function of total velocity. A diagram of a typical spherical probe

sensing head is presented in Figure 2F-4. Typical probe dimensions are indicated in the illustration.

6.1.3 *A manual 3-D probe* refers to a five-hole prism-shaped or spherical probe that is positioned at individual traverse points and yaw nulled manually by an operator. An automated 3-D probe refers to a system that uses a computer-controlled motorized mechanism to position the five-hole prism-shaped or spherical head at individual traverse points and perform yaw angle determinations.

6.1.4 *Other three-dimensional probes.* [Reserved]

6.1.5 *Probe sheath.* The probe shaft shall include an outer sheath to: (1) provide a surface for inscribing a permanent reference scribe line, (2) accommodate attachment of an angle-measuring device to the probe shaft, and (3) facilitate precise rotational movement of the probe for determining yaw angles. The sheath shall be rigidly attached to the probe assembly and shall enclose all pressure lines from the probe head to the farthest position away from the probe head where an angle-measuring device may be attached during use in the field. The sheath of the fully assembled probe shall be sufficiently rigid and straight at all rotational positions such that, when one end of the probe shaft is held in a horizontal position, the fully extended probe meets the horizontal straightness specifications indicated in section 8.2 below.

6.1.6 *Scribe lines.*

6.1.6.1 *Reference scribe line.* A permanent line, no greater than 1.6 mm (1/16 in.) in width, shall be inscribed on each manual probe that will be used to determine yaw angles of flow. This line shall be placed on the main probe sheath in accordance with the procedures described in section 10.4 and is used as a reference position for installation of the yaw angle-measuring device on the probe. At the discretion of the tester, the scribe line may be a single line segment placed at a particular position on the probe sheath (e.g., near the probe head), multiple line segments placed at various locations along the length of the probe sheath (e.g., at every position where a yaw angle-measuring device may be mounted), or a single continuous line extending along the full length of the probe sheath.

6.1.6.2 *Scribe line on probe extensions.* A permanent line may also be inscribed on any probe extension that will be attached to the main probe in performing field testing. This allows a yaw angle-measuring device mounted on the extension to be readily aligned with the reference scribe line on the main probe sheath.

6.1.6.3 *Alignment specifications.* This specification shall be met separately, using the procedures in section 10.4.1, on the main probe and on each probe extension. The rotational position of the scribe line or scribe line segments on the main probe or any probe extension must not vary by more than 2°. That is, the difference between the minimum and maximum of all of the rotational angles that are measured along the full length of the main probe or the probe extension must not exceed 2°.

6.1.7 Probe and system characteristics to ensure horizontal stability.

6.1.7.1 For manual probes, it is recommended that the effective length of the probe (coupled with a probe extension, if necessary) be at least 0.9 m (3 ft.) longer than the farthest traverse point mark on the probe shaft away from the probe head. The operator should maintain the probe's horizontal stability when it is fully inserted into the stack or duct. If a shorter probe is used, the probe should be inserted through a bushing sleeve, similar to the one shown in Figure 2F-5, that is installed on the test port; such a bushing shall fit snugly around the probe and be secured to the stack or duct entry port in such a manner as to maintain the probe's horizontal stability when fully inserted into the stack or duct.

6.1.7.2 An automated system that includes an external probe casing with a transport system shall have a mechanism for maintaining horizontal stability comparable to that obtained by manual probes following the provisions of this method. The automated probe assembly shall also be constructed to maintain the alignment and position of the pressure ports during sampling at each traverse point. The design of the probe casing and transport system shall allow the probe to be removed from the stack or duct and checked through direct physical measurement for angular position and insertion depth.

6.1.8 The tubing that is used to connect the probe and the pressure-measuring device should have an inside diameter of at least 3.2 mm (1/8 in.), to reduce the time required for pressure equilibration, and should be as short as practicable.

6.2 Yaw Angle-measuring Device. One of the following devices shall be used for measurement of the yaw angle of flow.

6.2.1 Digital inclinometer. This refers to a digital device capable of measuring and displaying the rotational position of the probe to within $\pm 1^\circ$. The device shall be able to be locked into position on the probe sheath or probe extension, so that it indicates the probe's rotational position throughout the test. A rotational position collar block that can be attached to the probe sheath (similar to the collar shown in Figure 2F-6) may be required to lock the digital inclinometer into position on the probe sheath.

6.2.2 Protractor wheel and pointer assembly. This apparatus, similar to that shown in Figure 2F-7, consists of the following components.

6.2.2.1 A protractor wheel that can be attached to a port opening and set in a fixed rotational position to indicate the yaw angle position of the probe's scribe line relative to the longitudinal axis of the stack or duct. The protractor wheel must have a measurement ring on its face that is no less than 17.8 cm (7 in.) in diameter, shall be able to be rotated to any angle and then locked into position on the stack or duct port, and shall indicate angles to a resolution of 1° .

6.2.2.2 A pointer assembly that includes an indicator needle mounted on a collar that can slide over the probe sheath and be locked into a fixed rotational position on the probe sheath. The pointer needle shall be of sufficient length, rigidity, and sharpness to allow the tester to determine the probe's angular position to within 1° from the markings on the protractor wheel. Corresponding to the position of the pointer, the collar must have a scribe line to be used in aligning the pointer with the scribe line on the probe sheath.

6.2.3 Other yaw angle-measuring devices. Other angle-measuring devices with a manufacturer's specified precision of 1° or better may be used, if approved by the Administrator.

6.3 Probe Supports and Stabilization Devices. When probes are used for determining flow angles, the probe head should be kept in a stable horizontal position. For probes longer than 3.0 m (10 ft.), the section of the probe that extends outside the test port shall be secured. Three alternative devices are suggested for maintaining the horizontal position and stability of the probe shaft during flow angle determinations and velocity pressure measurements: (1) Monorails installed above each port, (2) probe stands on which the probe shaft may be rested, or (3) bushing sleeves of sufficient length secured to the test ports to maintain probes in a horizontal position. Comparable provisions shall be made to ensure that automated systems maintain the horizontal position of the probe in the stack or duct. The physical characteristics of each test platform may dictate the most suitable type of stabilization device. Thus, the choice of a specific stabilization device is left to the judgment of the testers.

6.4 Differential Pressure Gauges. The pressure (ΔP) measuring devices used during wind tunnel calibrations and field testing shall be either electronic manometers (e.g., pressure transducers), fluid manometers, or mechanical pressure gauges (e.g., Magnehelic^Δ gauges). Use of electronic manometers is recommended. Under low velocity conditions, use of electronic manometers may be necessary to obtain acceptable measurements.

6.4.1 Differential pressure-measuring device. This refers to a device capable of measuring pressure differentials and having a readability of ± 1 percent of full scale. The device shall be capable of accurately measuring the maximum expected pressure differential. Such devices are used to determine the following pressure measurements: velocity pressure, static pressure, yaw-null pressure, and pitch-angle pressure. For an inclined-vertical manometer, the readability specification of ± 1 percent shall be met separately using the respective full-scale upper limits of the inclined and vertical portions of the scales. To the extent practicable, the device shall be selected such that most of the pressure readings are between 10 and 90 percent of the device's full-scale measurement range (as defined in section 3.5). Typical velocity pressure (P_1-P_2) ranges for both the prism-shaped probe and the spherical probe are 0 to 1.3 cm H₂O (0 to 0.5 in. H₂O), 0 to 5.1 cm H₂O (0 to 2 in. H₂O), and 0 to 12.7 cm H₂O (0 to 5 in. H₂O). The pitch angle (P_4-P_5) pressure range is typically -6.4 to $+6.4$ mm H₂O (-0.25 to $+0.25$ in. H₂O) or -12.7 to $+12.7$ mm H₂O (-0.5 to $+0.5$ in. H₂O) for the prism-shaped probe, and -12.7 to $+12.7$ mm H₂O (-0.5 to $+0.5$ in. H₂O) or -5.1 to $+5.1$ cm H₂O (-2 to $+2$ in. H₂O) for the spherical probe. The pressure range for the yaw null (P_2-P_3) readings is typically -12.7 to $+12.7$ mm H₂O (-0.5 to $+0.5$ in. H₂O) for both probe types. In addition, pressure-measuring devices should be selected such that the zero does not drift by more than 5 percent of the average expected pressure readings to be encountered during the field test. This is particularly important under low pressure conditions.

6.4.2 Gauge used for yaw nulling. The differential pressure-measuring device chosen for yaw nulling the probe during the wind tunnel calibrations and field testing shall be bi-directional, i.e., capable of reading both positive and negative differential pressures. If a mechanical, bi-directional pressure gauge is chosen, it shall have a full-scale range no greater than 2.6 cm H₂O (1 in. H₂O) [i.e., -1.3 to $+1.3$ cm H₂O (-0.5 in. to $+0.5$ in.)].

6.4.3 Devices for calibrating differential pressure-measuring devices. A precision manometer (e.g., a U-tube, inclined, or inclined-vertical manometer, or micromanometer) or NIST (National Institute of Standards and Technology) traceable pressure source shall be used for calibrating differential pressure-measuring devices. The device shall be maintained under laboratory conditions or in a similar protected environment (e.g., a climate-controlled trailer). It shall not be used in field tests. The precision manometer shall have a scale gradation of 0.3 mm H₂O (0.01 in. H₂O), or less, in the range of 0 to 5.1 cm H₂O (0 to 2 in. H₂O) and 2.5 mm H₂O (0.1 in. H₂O), or less, in the range of 5.1 to 25.4 cm H₂O (2 to 10 in. H₂O). The manometer shall have manufacturer's documentation that it meets an accuracy specification of at least 0.5 percent of full scale. The NIST-traceable pressure source shall be recertified annually.

6.4.4 Devices used for post-test calibration check. A precision manometer meeting the specifications in section 6.4.3, a pressure-measuring device or pressure source with a documented calibration traceable to NIST, or an equivalent device approved by the Administrator shall be used for the post-test calibration check. The pressure-measuring device shall have a readability equivalent to or greater than the tested device. The pressure source shall be capable of generating pressures between 50 and 90 percent of the range of the tested device and known to within ± 1 percent of the full scale of the tested device. The pressure source shall be recertified annually.

6.5 Data Display and Capture Devices. Electronic manometers (if used) shall be coupled with a data display device (such as a digital panel meter, personal computer display, or strip chart) that allows the tester to observe and validate the pressure measurements taken during testing. They shall also be connected to a data recorder (such as a data logger or a personal computer with data capture software) that has the ability to compute and retain the appropriate average value at each traverse point, identified by collection time and traverse point.

6.6 Temperature Gauges. For field tests, a thermocouple or resistance temperature detector (RTD) capable of measuring temperature to within $\pm 3^{\circ}\text{C}$ ($\pm 5^{\circ}\text{F}$) of the stack or duct temperature shall be used. The thermocouple shall be attached to the probe such that the sensor tip does not touch any metal and is located on the opposite side of the probe head from the pressure ports so as not to interfere with the gas flow around the probe head. The position of the thermocouple relative to the pressure port face openings shall be in the same configuration as used for the probe calibrations in the wind tunnel. Temperature gauges used for wind tunnel calibrations shall be capable of measuring temperature to within $\pm 0.6^{\circ}\text{C}$ ($\pm 1^{\circ}\text{F}$) of the temperature of the flowing gas stream in the wind tunnel.

6.7 Stack or Duct Static Pressure Measurement. The pressure-measuring device used with the probe shall be as specified in section 6.4 of this method. The static tap of a standard (Prandtl type) pitot tube or one leg of a Type S pitot tube with the face opening planes positioned parallel to the gas flow may be used for this measurement. Also acceptable is the pressure differential reading of $P_1 - P_{\text{bar}}$ from a five-hole prism-shaped probe (e.g., Type DA or DAT probe) with the P_1 pressure port face opening positioned parallel to the gas flow in the same manner as the Type S probe. However, the spherical probe, as specified in section 6.1.2, is unable to provide this measurement and shall not be used to take static pressure measurements. Static pressure measurement is further described in section 8.11.

6.8 Barometer. Same as Method 2, section 2.5.

6.9 Gas Density Determination Equipment. Method 3 or 3A shall be used to determine the dry molecular weight of the stack gas. Method 4 shall be used for moisture content determination and computation of stack gas wet molecular weight. Other methods may be used, if approved by the Administrator.

6.10 Calibration Pitot Tube. Same as Method 2, section 2.7.

6.11 Wind Tunnel for Probe Calibration. Wind tunnels used to calibrate velocity probes must meet the following design specifications.

6.11.1 Test section cross-sectional area. The flowing gas stream shall be confined within a circular, rectangular, or elliptical duct. The cross-sectional area of the tunnel must be large enough to ensure fully developed flow in the presence of both the calibration pitot tube and the tested probe. The calibration site, or "test section," of the wind tunnel shall have a minimum diameter of 30.5 cm (12 in.) for circular or elliptical duct cross-sections or a minimum width of 30.5 cm (12 in.) on the shorter side for rectangular cross-sections. Wind tunnels shall meet the probe blockage provisions of this section and the qualification requirements prescribed in section 10.1. The projected area of the portion of the probe head, shaft, and attached devices inside the wind tunnel during calibration shall represent no more than 4 percent of the cross-sectional area of the tunnel. The projected area shall include the combined area of the calibration pitot tube and the tested probe if both probes are placed simultaneously in the same cross-sectional plane in the wind tunnel, or the larger projected area of the two probes if they are placed alternately in the wind tunnel.

6.11.2 Velocity range and stability. The wind tunnel should be capable of maintaining velocities between 6.1 m/sec and 30.5 m/sec (20 ft/sec and 100 ft/sec). The wind tunnel shall produce fully developed flow patterns that are stable and parallel to the axis of the duct in the test section.

6.11.3 Flow profile at the calibration location. The wind tunnel shall provide axial flow within the test section calibration location (as defined in section 3.20). Yaw and pitch angles in the calibration location shall be within $\pm 3^\circ$ of 0° . The procedure for determining that this requirement has been met is described in section 10.1.2.

6.11.4 Entry ports in the wind tunnel test section.

6.11.4.1 Port for tested probe. A port shall be constructed for the tested probe. The port should have an elongated slot parallel to the axis of the duct at the test section. The elongated slot should be of sufficient length to allow attaining all the pitch angles at which the probe will be calibrated for use in the field. To facilitate alignment of the probe during calibration, the test section should include a window constructed of a transparent material to allow the tested probe to be viewed. This port shall be located to allow the head of the tested probe to be positioned within the calibration location (as defined in section 3.20) at all pitch angle settings.

6.11.4.2 Port for verification of axial flow. Depending on the equipment selected to conduct the axial flow verification prescribed in section 10.1.2, a second port, located 90° from the entry port for the tested probe, may be needed to allow verification that the gas flow is parallel to the central axis of the test section. This port should be located and constructed so as to allow one of the probes described in section 10.1.2.2 to access the same test point(s) that are accessible from the port described in section 6.11.4.1.

6.11.4.3 Port for calibration pitot tube. The calibration pitot tube shall be used in the port for the tested probe or a separate entry port. In either case, all measurements with the calibration pitot tube shall be made at the same point within the wind tunnel over the course of a probe calibration. The measurement point for the calibration pitot tube shall meet the same specifications for distance from the wall and for axial flow as described in section 3.20 for the wind tunnel calibration location.

6.11.5 Pitch angle protractor plate. A protractor plate shall be attached directly under the port used with the tested probe and set in a fixed position to indicate the pitch angle position of the probe relative to the longitudinal axis of the wind tunnel duct (similar to Figure 2F–8). The protractor plate shall indicate angles in 5° increments with a minimum resolution of $\pm 2^\circ$. The tested probe shall be able to be locked into position at the desired pitch angle delineated on the protractor. The probe head position shall be maintained within the calibration location (as defined in section 3.20) in the test section of the wind tunnel during all tests across the range of pitch angles.

7.0 Reagents and Standards[Reserved]

8.0 Sample Collection and Analysis

8.1 Equipment Inspection and Set-Up

8.1.1 All probes, differential pressure-measuring devices, yaw angle-measuring devices, thermocouples, and barometers shall have a current, valid calibration before being used in a field test. (See sections 10.3.3, 10.3.4, and 10.5 through 10.10 for the applicable calibration requirements.)

8.1.2 Before each field use of a 3-D probe, perform a visual inspection to verify the physical condition of the probe head according to the procedures in section 10.2. Record the inspection results on a form similar to Table 2F–1. If there is visible damage to the 3-D probe, the probe shall not be used until it is recalibrated.

8.1.3 After verifying that the physical condition of the probe head is acceptable, set up the apparatus using lengths of flexible tubing that are as short as practicable. Surge tanks installed between the probe and pressure-measuring device may be used to dampen pressure fluctuations provided that an adequate measurement response time (see section 8.8) is maintained.

8.2 Horizontal Straightness Check. A horizontal straightness check shall be performed before the start of each field test, except as otherwise specified in this section. Secure the fully assembled

probe (including the probe head and all probe shaft extensions) in a horizontal position using a stationary support at a point along the probe shaft approximating the location of the stack or duct entry port when the probe is sampling at the farthest traverse point from the stack or duct wall. The probe shall be rotated to detect bends. Use an angle-measuring device or trigonometry to determine the bend or sag between the probe head and the secured end. (See Figure 2F–9.) Probes that are bent or sag by more than 5° shall not be used. Although this check does not apply when the probe is used for a vertical traverse, care should be taken to avoid the use of bent probes when conducting vertical traverses. If the probe is constructed of a rigid steel material and consists of a main probe without probe extensions, this check need only be performed before the initial field use of the probe, when the probe is recalibrated, when a change is made to the design or material of the probe assembly, and when the probe becomes bent. With such probes, a visual inspection shall be made of the fully assembled probe before each field test to determine if a bend is visible. The probe shall be rotated to detect bends. The inspection results shall be documented in the field test report. If a bend in the probe is visible, the horizontal straightness check shall be performed before the probe is used.

8.3 Rotational Position Check. Before each field test, and each time an extension is added to the probe during a field test, a rotational position check shall be performed on all manually operated probes (except as noted in section 8.3.5, below) to ensure that, throughout testing, the angle-measuring device is either: aligned to within $\pm 1^\circ$ of the rotational position of the reference scribe line; or is affixed to the probe such that the rotational offset of the device from the reference scribe line is known to within $\pm 1^\circ$. This check shall consist of direct measurements of the rotational positions of the reference scribe line and angle-measuring device sufficient to verify that these specifications are met. Annex A in section 18 of this method gives recommended procedures for performing the rotational position check, and Table 2F–2 gives an example data form. Procedures other than those recommended in Annex A in section 18 may be used, provided they demonstrate whether the alignment specification is met and are explained in detail in the field test report.

8.3.1 Angle-measuring device rotational offset. The tester shall maintain a record of the angle-measuring device rotational offset, R_{ADO} , as defined in section 3.1. Note that R_{ADO} is assigned a value of 0° when the angle-measuring device is aligned to within $\pm 1^\circ$ of the rotational position of the reference scribe line. The R_{ADO} shall be used to determine the yaw angle of flow in accordance with section 8.9.4.

8.3.2 Sign of angle-measuring device rotational offset. The sign of R_{ADO} is positive when the angle-measuring device (as viewed from the “tail” end of the probe) is positioned in a clockwise direction from the reference scribe line and negative when the device is positioned in a counterclockwise direction from the reference scribe line.

8.3.3 Angle-measuring devices that can be independently adjusted (e.g., by means of a set screw), after being locked into position on the probe sheath, may be used. However, the R_{ADO} must also take into account this adjustment.

8.3.4 Post-test check. If probe extensions remain attached to the main probe throughout the field test, the rotational position check shall be repeated, at a minimum, at the completion of the field

test to ensure that the angle-measuring device has remained within $\pm 2^\circ$ of its rotational position established prior to testing. At the discretion of the tester, additional checks may be conducted after completion of testing at any sample port or after any test run. If the $\pm 2^\circ$ specification is not met, all measurements made since the last successful rotational position check must be repeated. Section 18.1.1.3 of Annex A provides an example procedure for performing the post-test check.

8.3.5 Exceptions.

8.3.5.1 A rotational position check need not be performed if, for measurements taken at all velocity traverse points, the yaw angle-measuring device is mounted and aligned directly on the reference scribe line specified in sections 6.1.6.1 and 6.1.6.3 and no independent adjustments, as described in section 8.3.3, are made to the device's rotational position.

8.3.5.2 If extensions are detached and re-attached to the probe during a field test, a rotational position check need only be performed the first time an extension is added to the probe, rather than each time the extension is re-attached, if the probe extension is designed to be locked into a mechanically fixed rotational position (e.g., through use of interlocking grooves) that can re-establish the initial rotational position to within $\pm 1^\circ$.

8.4 Leak Checks. A pre-test leak check shall be conducted before each field test. A post-test check shall be performed at the end of the field test, but additional leak checks may be conducted after any test run or group of test runs. The post-test check may also serve as the pre-test check for the next group of test runs. If any leak check is failed, all runs since the last passed leak check are invalid. While performing the leak check procedures, also check each pressure device's responsiveness to the changes in pressure.

8.4.1 To perform the leak check, pressurize the probe's P_1 pressure port until at least 7.6 cm H_2O (3 in. H_2O) pressure, or a pressure corresponding to approximately 75 percent of the pressure-measuring device's measurement scale, whichever is less, registers on the device; then, close off the pressure port. The pressure shall remain stable [± 2.5 mm H_2O (± 0.10 in. H_2O)] for at least 15 seconds. Check the P_2 , P_3 , P_4 , and P_5 pressure ports in the same fashion. Other leak-check procedures may be used, if approved by the Administrator.

8.5 Zeroing the Differential Pressure-measuring Device. Zero each differential pressure-measuring device, including the device used for yaw nulling, before each field test. At a minimum, check the zero after each field test. A zero check may also be performed after any test run or group of test runs. For fluid manometers and mechanical pressure gauges (e.g., Magnehelic^Δ gauges), the zero reading shall not deviate from zero by more than ± 0.8 mm H_2O (± 0.03 in. H_2O) or one minor scale division, whichever is greater, between checks. For electronic manometers, the zero reading shall not deviate from zero between checks by more than: ± 0.3 mm H_2O (± 0.01 in. H_2O), for full scales less than or equal to 5.1 cm H_2O (2.0 in. H_2O); or ± 0.8 mm H_2O (± 0.03 in. H_2O), for full scales greater than 5.1 cm H_2O (2.0 in. H_2O). (Note: If negative zero drift is not directly readable, estimate the reading based on the position of the gauge oil in the manometer or of the needle on the pressure gauge.) In addition, for all pressure-measuring devices except those used exclusively for yaw nulling, the zero reading shall not deviate from zero by more than 5 percent of the average measured differential pressure at any

distinct process condition or load level. If any zero check is failed at a specific process condition or load level, all runs conducted at that process condition or load level since the last passed zero check are invalid.

8.6 Traverse Point Verification. The number and location of the traverse points shall be selected based on Method 1 guidelines. The stack or duct diameter and port nipple lengths, including any extension of the port nipples into stack or duct, shall be verified the first time the test is performed; retain and use this information for subsequent field tests, updating it as required. Physically measure the stack or duct dimensions or use a calibrated laser device; do not use engineering drawings of the stack or duct. The probe length necessary to reach each traverse point shall be recorded to within ± 6.4 mm ($\pm 1/4$ in.) and, for manual probes, marked on the probe sheath. In determining these lengths, the tester shall take into account both the distance that the port flange projects outside of the stack and the depth that any port nipple extends into the gas stream. The resulting point positions shall reflect the true distances from the inside wall of the stack or duct, so that when the tester aligns any of the markings with the outside face of the stack port, the probe's impact port shall be located at the appropriate distance from the inside wall for the respective Method 1 traverse point. Before beginning testing at a particular location, an out-of-stack or duct verification shall be performed on each probe that will be used to ensure that these position markings are correct. The distances measured during the verification must agree with the previously calculated distances to within $\pm 1/4$ in. For manual probes, the traverse point positions shall be verified by measuring the distance of each mark from the probe's P_1 pressure port. A comparable out-of-stack test shall be performed on automated probe systems. The probe shall be extended to each of the prescribed traverse point positions. Then, the accuracy of the positioning for each traverse point shall be verified by measuring the distance between the port flange and the probe's P_1 pressure port.

8.7 Probe Installation. Insert the probe into the test port. A solid material shall be used to seal the port.

8.8 System Response Time. Determine the response time of the probe measurement system. Insert and position the "cold" probe (at ambient temperature and pressure) at any Method 1 traverse point. Read and record the probe's P_1 - P_2 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.

8.9 Sampling.

8.9.1 Yaw angle measurement protocol. With manual probes, yaw angle measurements may be obtained in two alternative ways during the field test, either by using a yaw angle-measuring device (e.g., digital inclinometer) affixed to the probe, or using a protractor wheel and pointer assembly. For horizontal traversing, either approach may be used. For vertical traversing, i.e., when measuring from on top or into the bottom of a horizontal duct, only the protractor wheel and pointer assembly may be used. With automated probes, curve-fitting protocols may be used to obtain yaw-angle measurements.

8.9.1.1 If a yaw angle-measuring device affixed to the probe is to be used, lock the device on the probe sheath, aligning it either on the reference scribe line or in the rotational offset position established under section 8.3.1.

8.9.1.2 If a protractor wheel and pointer assembly is to be used, follow the procedures in Annex B of this method.

8.9.1.3 Other yaw angle-determination procedures. If approved by the Administrator, other procedures for determining yaw angle may be used, provided that they are verified in a wind tunnel to be able to perform the yaw angle calibration procedure as described in section 10.5.

8.9.2 Sampling strategy. At each traverse point, first yaw-null the probe, as described in section 8.9.3, below. Then, with the probe oriented into the direction of flow, measure and record the yaw angle, the differential pressures and the temperature at the traverse point, after stable readings are achieved, in accordance with sections 8.9.4 and 8.9.5. At the start of testing in each port (i.e., after a probe has been inserted into the flue 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 flue 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.

8.9.3 Yaw-nulling procedure. In preparation for yaw angle determination, the probe must first be yaw nulled. After positioning the probe at the appropriate traverse point, perform the following procedures.

8.9.3.1 Rotate the probe until a null differential pressure reading (the difference in pressures across the P_2 and P_3 pressure ports is zero (i.e., $P_2=P_3$) is indicated by the yaw angle pressure gauge. Read and record the angle displayed by the angle-measuring device.

8.9.3.2 Sign of the measured angle. The angle displayed on the angle-measuring device is considered positive when the probe's impact pressure port (as viewed from the "tail" end of the probe) is oriented in a clockwise rotational position relative to the stack or duct axis and is considered negative when the probe's impact pressure port is oriented in a counterclockwise rotational position (see Figure 2F-10).

8.9.4 Yaw angle determination. After performing the yaw-nulling procedure in section 8.9.3, determine the yaw angle of flow according to one of the following procedures. Special care must be observed to take into account the signs of the recorded angle and all offsets.

8.9.4.1 Direct-reading. If all rotational offsets are zero or if the angle-measuring device rotational offset (R_{ADO}) determined in section 8.3 exactly compensates for the scribe line rotational offset (R_{SLO}) determined in section 10.5, then the magnitude of the yaw angle is equal to the displayed angle-measuring device reading from section 8.9.3.1. The algebraic sign of the yaw angle is determined in accordance with section 8.9.3.2.

Note: Under certain circumstances (e.g., testing of horizontal ducts), a 90° adjustment to the angle-measuring device readings may be necessary to obtain the correct yaw angles.

8.9.4.2 Compensation for rotational offsets during data reduction. When the angle-measuring device rotational offset does not compensate for reference scribe line rotational offset, the following procedure shall be used to determine the yaw angle:

- (a) Enter the reading indicated by the angle-measuring device from section 8.9.3.1.
- (b) Associate the proper algebraic sign from section 8.9.3.2 with the reading in step (a).
- (c) Subtract the reference scribe line rotational offset, R_{SLO} , from the reading in step (b).
- (d) Subtract the angle-measuring device rotational offset, R_{ADO} , if any, from the result obtained in step (c).
- (e) The final result obtained in step (d) is the yaw angle of flow.

Note: It may be necessary to first apply a 90° adjustment to the reading in step (a), in order to obtain the correct yaw angle.

8.9.4.3 Record the yaw angle measurements on a form similar to Table 2F-3.

8.9.5 Velocity determination. Maintain the probe rotational position established during the yaw angle determination. Then, begin recording the pressure-measuring device readings for the impact pressure (P_1 - P_2) and pitch angle pressure (P_4 - P_5). These pressure measurements shall be taken over a sampling period of sufficiently long duration to ensure representative readings at each traverse point. If the pressure measurements are determined from visual readings of the pressure device or display, allow sufficient time to observe the pulsation in the readings to obtain a sight-weighted average, which is then recorded manually. If an automated data acquisition system (e.g., data logger, computer-based data recorder, strip chart recorder) is used to record the pressure measurements, obtain an integrated average of all pressure readings at the traverse point. Stack or duct gas temperature measurements shall be recorded, at a minimum, once at each traverse point. Record all necessary data as shown in the example field data form (Table 2F-3).

8.9.6 Alignment check. For manually operated probes, after the required yaw angle and differential pressure and temperature measurements have been made at each traverse point, verify (e.g., by visual inspection) that the yaw angle-measuring device has remained in proper alignment with the reference scribe line or with the rotational offset position established in section 8.3. If, for a particular traverse point, the angle-measuring device is found to be in proper alignment, proceed to the next traverse point; otherwise, re-align the device and repeat the angle and differential pressure measurements at the traverse point. In the course of a traverse, if a mark used to properly align the angle-measuring device (e.g., as described in section 18.1.1.1) cannot be located, re-establish the alignment mark before proceeding with the traverse.

8.10 Probe Plugging. Periodically check for plugging of the pressure ports by observing the responses on pressure differential readouts. Plugging causes erratic results or sluggish responses. Rotate the probe to determine whether the readouts respond in the expected direction. If plugging is detected, correct the problem and repeat the affected measurements.

8.11 Static Pressure. Measure the static pressure in the stack or duct using the equipment described in section 6.7.

8.11.1 If a Type DA or DAT probe is used for this measurement, position the probe at or between any traverse point(s) and rotate the probe until a null differential pressure reading is obtained at P_2 - P_3 . Rotate the probe 90° . Disconnect the P_2 pressure side of the probe and read the pressure P_1 - P_{bar} and record as the static pressure. (Note: The spherical probe, specified in section 6.1.2, is unable to provide this measurement and shall not be used to take static pressure measurements.)

8.11.2 If a Type S probe is used for this measurement, position the probe at or between any traverse point(s) and rotate the probe until a null differential pressure reading is obtained. Disconnect the tubing from one of the pressure ports; read and record the ΔP . For pressure devices with one-directional scales, if a deflection in the positive direction is noted with the negative side disconnected, then the static pressure is positive. Likewise, if a deflection in the positive direction is noted with the positive side disconnected, then the static pressure is negative.

8.12 Atmospheric Pressure. Determine the atmospheric pressure at the sampling elevation during each test run following the procedure described in section 2.5 of Method 2.

8.13 Molecular Weight. Determine the stack gas dry molecular weight. For combustion processes or processes that emit essentially CO_2 , O_2 , CO , and N_2 , use Method 3 or 3A. For processes emitting essentially air, an analysis need not be conducted; use a dry molecular weight of 29.0. Other methods may be used, if approved by the Administrator.

8.14 Moisture. Determine the moisture content of the stack gas using Method 4 or equivalent.

8.15 Data Recording and Calculations. Record all required data on a form similar to Table 2F-3.

8.15.1 Selection of appropriate calibration curves. Choose the appropriate pair of F_1 and F_2 versus pitch angle calibration curves, created as described in section 10.6.

8.15.2 Pitch angle derivation. Use the appropriate calculation procedures in section 12.2 to find the pitch angle ratios that are applicable at each traverse point. Then, find the pitch angles corresponding to these pitch angle ratios on the " F_1 versus pitch angle" curve for the probe.

8.15.3 Velocity calibration coefficient derivation. Use the pitch angle obtained following the procedures described in section 8.15.2 to find the corresponding velocity calibration coefficients from the " F_2 versus pitch angle" calibration curve for the probe.

8.15.4 Calculations. Calculate the axial velocity at each traverse point using the equations presented in section 12.2 to account for the yaw and pitch angles of flow. Calculate the test run average stack gas velocity by finding the arithmetic average of the point velocity results in accordance with sections 12.3 and 12.4, and calculate the stack gas volumetric flow rate in accordance with section 12.5 or 12.6, as applicable.

9.0 Quality Control

9.1 Quality Control Activities. In conjunction with the yaw angle determination and the pressure and temperature measurements specified in section 8.9, the following quality control checks should be performed.

9.1.1 Range of the differential pressure gauge. In accordance with the specifications in section 6.4, ensure that the proper differential pressure gauge is being used for the range of ΔP values encountered. If it is necessary to change to a more sensitive gauge, replace the gauge with a gauge calibrated according to section 10.3.3, perform the leak check described in section 8.4 and the zero check described in section 8.5, and repeat the differential pressure and temperature readings at each traverse point.

9.1.2 Horizontal stability check. For horizontal traverses of a stack or duct, visually check that the probe shaft is maintained in a horizontal position prior to taking a pressure reading. Periodically, during a test run, the probe's horizontal stability should be verified by placing a carpenter's level, a digital inclinometer, or other angle-measuring device on the portion of the probe sheath that extends outside of the test port. A comparable check should be performed by automated systems.

10.0 Calibration

10.1 Wind Tunnel Qualification Checks. To qualify for use in calibrating probes, a wind tunnel shall have the design features specified in section 6.11 and satisfy the following qualification criteria. The velocity pressure cross-check in section 10.1.1 and axial flow verification in section 10.1.2 shall be performed before the initial use of the wind tunnel and repeated immediately after any alteration occurs in the wind tunnel's configuration, fans, interior surfaces, straightening vanes, controls, or other properties that could reasonably be expected to alter the flow pattern or velocity stability in the tunnel. The owner or operator of a wind tunnel used to calibrate probes according to this method shall maintain records documenting that the wind tunnel meets the requirements of sections 10.1.1 and 10.1.2 and shall provide these records to the Administrator upon request.

10.1.1 Velocity pressure cross-check. To verify that the wind tunnel produces the same velocity at the tested probe head as at the calibration pitot tube impact port, perform the following cross-check. Take three differential pressure measurements at the fixed calibration pitot tube location, using the calibration pitot tube specified in section 6.10, and take three measurements with the calibration pitot tube at the wind tunnel calibration location, as defined in section 3.20. Alternate the measurements between the two positions. Perform this procedure at the lowest and highest velocity settings at which the probes will be calibrated. Record the values on a form similar to

Table 2F–4. At each velocity setting, the average velocity pressure obtained at the wind tunnel calibration location shall be within ± 2 percent or 2.5 mm H₂O (0.01 in. H₂O), whichever is less restrictive, of the average velocity pressure obtained at the fixed calibration pitot tube location. This comparative check shall be performed at 2.5-cm (1-in.), or smaller, intervals across the full length, width, and depth (if applicable) of the wind tunnel calibration location. If the criteria are not met at every tested point, the wind tunnel calibration location must be redefined, so that acceptable results are obtained at every point. Include the results of the velocity pressure cross-check in the calibration data section of the field test report. (See section 16.1.4.)

10.1.2 Axial flow verification. The following procedures shall be performed to demonstrate that there is fully developed axial flow within the calibration location and at the calibration pitot tube location. Two testing options are available to conduct this check.

10.1.2.1 Using a calibrated 3–D probe. A 3–D probe that has been previously calibrated in a wind tunnel with documented axial flow (as defined in section 3.21) may be used to conduct this check. Insert the calibrated 3–D probe into the wind tunnel test section using the tested probe port. Following the procedures in sections 8.9 and 12.2 of this method, determine the yaw and pitch angles at all the point(s) in the test section where the velocity pressure cross-check, as specified in section 10.1.1, is performed. This includes all the points in the calibration location and the point where the calibration pitot tube will be located. Determine the yaw and pitch angles at each point. Repeat these measurements at the highest and lowest velocities at which the probes will be calibrated. Record the values on a form similar to Table 2F–5. Each measured yaw and pitch angle shall be within $\pm 3^\circ$ of 0° . Exceeding the limits indicates unacceptable flow in the test section. Until the problem is corrected and acceptable flow is verified by repetition of this procedure, the wind tunnel shall not be used for calibration of probes. Include the results of the axial flow verification in the calibration data section of the field test report. (See section 16.1.4.)

10.1.2.2 Using alternative probes. Axial flow verification may be performed using an uncalibrated prism-shaped 3–D probe (e.g., DA or DAT probe) or an uncalibrated wedge probe. (Figure 2F–11 illustrates a typical wedge probe.) This approach requires use of two ports: the tested probe port and a second port located 90° from the tested probe port. Each port shall provide access to all the points within the wind tunnel test section where the velocity pressure cross-check, as specified in section 10.1.1, is conducted. The probe setup shall include establishing a reference yaw-null position on the probe sheath to serve as the location for installing the angle-measuring device. Physical design features of the DA, DAT, and wedge probes are relied on to determine the reference position. For the DA or DAT probe, this reference position can be determined by setting a digital inclinometer on the flat facet where the P_1 pressure port is located and then identifying the rotational position on the probe sheath where a second angle-measuring device would give the same angle reading. The reference position on a wedge probe shaft can be determined either geometrically or by placing a digital inclinometer on each side of the wedge and rotating the probe until equivalent readings are obtained. With the latter approach, the reference position is the rotational position on the probe sheath where an angle-measuring device would give a reading of 0° . After installing the angle-measuring device in the reference yaw-null position on the probe sheath, determine the yaw angle from the tested port. Repeat this measurement using the 90° offset port, which provides the pitch angle of flow. Determine the yaw and pitch angles at all the point(s) in the test section where the velocity

pressure cross-check, as specified in section 10.1.1, is performed. This includes all the points in the wind tunnel calibration location and the point where the calibration pitot tube will be located. Perform this check at the highest and lowest velocities at which the probes will be calibrated. Record the values on a form similar to Table 2F-5. Each measured yaw and pitch angle shall be within $\pm 3^\circ$ of 0° . Exceeding the limits indicates unacceptable flow in the test section. Until the problem is corrected and acceptable flow is verified by repetition of this procedure, the wind tunnel shall not be used for calibration of probes. Include the results in the probe calibration report.

10.1.3 Wind tunnel audits.

10.1.3.1 Procedure. Upon the request of the Administrator, the owner or operator of a wind tunnel shall calibrate a 3-D audit probe in accordance with the procedures described in sections 10.3 through 10.6. The calibration shall be performed at two velocities and over a pitch angle range that encompasses the velocities and pitch angles typically used for this method at the facility. The resulting calibration data and curves shall be submitted to the Agency in an audit test report. These results shall be compared by the Agency to reference calibrations of the audit probe at the same velocity and pitch angle settings obtained at two different wind tunnels.

10.1.3.2 Acceptance criteria. The audited tunnel's calibration is acceptable if all of the following conditions are satisfied at each velocity and pitch setting for the reference calibration obtained from at least one of the wind tunnels. For pitch angle settings between -15° and $+15^\circ$, no velocity calibration coefficient (i.e., F_2) may differ from the corresponding reference value by more than 3 percent. For pitch angle settings outside of this range (i.e., less than -15° and greater than $+15^\circ$), no velocity calibration coefficient may differ by more than 5 percent from the corresponding reference value. If the acceptance criteria are not met, the audited wind tunnel shall not be used to calibrate probes for use under this method until the problems are resolved and acceptable results are obtained upon completion of a subsequent audit.

10.2 Probe Inspection. Before each calibration of a 3-D probe, carefully examine the physical condition of the probe head. Particular attention shall be paid to the edges of the pressure ports and the surfaces surrounding these ports. Any dents, scratches, or asymmetries on the edges of the pressure ports and any scratches or indentations on the surfaces surrounding the pressure ports shall be noted because of the potential effect on the probe's pressure readings. If the probe has been previously calibrated, compare the current condition of the probe's pressure ports and surfaces to the results of the inspection performed during the probe's most recent wind tunnel calibration. Record the results of this inspection on a form and in diagrams similar to Table 2F-1. The information in Table 2F-1 will be used as the basis for comparison during the probe head inspections performed before each subsequent field use.

10.3 Pre-Calibration Procedures. Prior to calibration, a scribe line shall have been placed on the probe in accordance with section 10.4. The yaw angle and velocity calibration procedures shall not begin until the pre-test requirements in sections 10.3.1 through 10.3.4 have been met.

10.3.1 Perform the horizontal straightness check described in section 8.2 on the probe assembly that will be calibrated in the wind tunnel.

10.3.2 Perform a leak check in accordance with section 8.4.

10.3.3 Except as noted in section 10.3.3.3, calibrate all differential pressure-measuring devices to be used in the probe calibrations, using the following procedures. At a minimum, calibrate these devices on each day that probe calibrations are performed.

10.3.3.1 Procedure. Before each wind tunnel use, all differential pressure-measuring devices shall be calibrated against the reference device specified in section 6.4.3 using a common pressure source. Perform the calibration at three reference pressures representing 30, 60, and 90 percent of the full-scale range of the pressure-measuring device being calibrated. For an inclined-vertical manometer, perform separate calibrations on the inclined and vertical portions of the measurement scale, considering each portion of the scale to be a separate full-scale range. [For example, for a manometer with a 0- to 2.5-cm H₂O (0- to 1-in. H₂O) inclined scale and a 2.5- to 12.7-cm H₂O (1- to 5-in. H₂O) vertical scale, calibrate the inclined portion at 7.6, 15.2, and 22.9 mm H₂O (0.3, 0.6, and 0.9 in. H₂O), and calibrate the vertical portion at 3.8, 7.6, and 11.4 cm H₂O (1.5, 3.0, and 4.5 in. H₂O).] Alternatively, for the vertical portion of the scale, use three evenly spaced reference pressures, one of which is equal to or higher than the highest differential pressure expected in field applications.

10.3.3.2 Acceptance criteria. At each pressure setting, the two pressure readings made using the reference device and the pressure-measuring device being calibrated shall agree to within ± 2 percent of full scale of the device being calibrated or 0.5 mm H₂O (0.02 in. H₂O), whichever is less restrictive. For an inclined-vertical manometer, these requirements shall be met separately using the respective full-scale upper limits of the inclined and vertical portions of the scale. Differential pressure-measuring devices not meeting the ± 2 percent of full scale or 0.5 mm H₂O (0.02 in. H₂O) calibration requirement shall not be used.

10.3.3.3 Exceptions. Any precision manometer that meets the specifications for a reference device in section 6.4.3 and that is not used for field testing does not require calibration, but must be leveled and zeroed before each wind tunnel use. Any pressure device used exclusively for yaw nulling does not require calibration, but shall be checked for responsiveness to rotation of the probe prior to each wind tunnel use.

10.3.4 Calibrate digital inclinometers on each day of wind tunnel or field testing (prior to beginning testing) using the following procedures. Calibrate the inclinometer according to the manufacturer's calibration procedures. In addition, use a triangular block (illustrated in Figure 2F-12) with a known angle, θ independently determined using a protractor or equivalent device, between two adjacent sides to verify the inclinometer readings.

Note: If other angle-measuring devices meeting the provisions of section 6.2.3 are used in place of a digital inclinometer, comparable calibration procedures shall be performed on such devices.)

Secure the triangular block in a fixed position. Place the inclinometer on one side of the block (side A) to measure the angle of inclination (R_1). Repeat this measurement on the adjacent side of the block (side B) using the inclinometer to obtain a second angle reading (R_2). The difference

of the sum of the two readings from 180° (i.e., $180^\circ - R_1 - R_2$) shall be within $\pm 2^\circ$ of the known angle, Θ .

10.4 Placement of Reference Scribe Line. Prior to the first calibration of a probe, a line shall be permanently inscribed on the main probe sheath to serve as a reference mark for determining yaw angles. Annex C in section 18 of this method gives a guideline for placement of the reference scribe line.

10.4.1 This reference scribe line shall meet the specifications in sections 6.1.6.1 and 6.1.6.3 of this method. To verify that the alignment specification in section 6.1.6.3 is met, secure the probe in a horizontal position and measure the rotational angle of each scribe line and scribe line segment using an angle-measuring device that meets the specifications in section 6.2.1 or 6.2.3. For any scribe line that is longer than 30.5 cm (12 in.), check the line's rotational position at 30.5-cm (12-in.) intervals. For each line segment that is 30.5 cm (12 in.) or less in length, check the rotational position at the two endpoints of the segment. To meet the alignment specification in section 6.1.6.3, the minimum and maximum of all of the rotational angles that are measured along the full length of the main probe must not differ by more than 2° .

Note: A short reference scribe line segment [e.g., 15.2 cm (6 in.) or less in length] meeting the alignment specifications in section 6.1.6.3 is fully acceptable under this method. See section 18.1.1.1 of Annex A for an example of a probe marking procedure, suitable for use with a short reference scribe line.

10.4.2 The scribe line should be placed on the probe first and then it's offset from the yaw-null position established (as specified in section 10.5). The rotational position of the reference scribe line relative to the yaw-null position of the probe, as determined by the yaw angle calibration procedure in section 10.5, is defined as the reference scribe line rotational offset, R_{SLO} . The reference scribe line rotational offset shall be recorded and retained as part of the probe's calibration record.

10.4.3 Scribe line for automated probes. A scribe line may not be necessary for an automated probe system if a reference rotational position of the probe is built into the probe system design. For such systems, a "flat" (or comparable, clearly identifiable physical characteristic) should be provided on the probe casing or flange plate to ensure that the reference position of the probe assembly remains in a vertical or horizontal position. The rotational offset of the flat (or comparable, clearly identifiable physical characteristic) needed to orient the reference position of the probe assembly shall be recorded and maintained as part of the automated probe system's specifications.

10.5 Yaw Angle Calibration Procedure. For each probe used to measure yaw angles with this method, a calibration procedure shall be performed in a wind tunnel meeting the specifications in section 10.1 to determine the rotational position of the reference scribe line relative to the probe's yaw-null position. This procedure shall be performed on the main probe with all devices that will be attached to the main probe in the field [such as thermocouples or resistance temperature detectors (RTDs)] that may affect the flow around the probe head. Probe shaft extensions that do

not affect flow around the probe head need not be attached during calibration. At a minimum, this procedure shall include the following steps.

10.5.1 Align and lock the angle-measuring device on the reference scribe line. If a marking procedure (such as that described in section 18.1.1.1) is used, align the angle-measuring device on a mark within $\pm 1^\circ$ of the rotational position of the reference scribe line. Lock the angle-measuring device onto the probe sheath at this position.

10.5.2 Zero the pressure-measuring device used for yaw nulling.

10.5.3 Insert the probe assembly into the wind tunnel through the entry port, positioning the probe's impact port at the calibration location. Check the responsiveness of the pressure-measurement device to probe rotation, taking corrective action if the response is unacceptable.

10.5.4 Ensure that the probe is in a horizontal position, using a carpenter's level.

10.5.5 Rotate the probe either clockwise or counterclockwise until a yaw null ($P_2=P_3$) is obtained.

10.5.6 Use the reading displayed by the angle-measuring device at the yaw-null position to determine the magnitude of the reference scribe line rotational offset, R_{SLO} , as defined in section 3.15. Annex D in section 18 of this method provides a recommended procedure for determining the magnitude of R_{SLO} with a digital inclinometer and a second procedure for determining the magnitude of R_{SLO} with a protractor wheel and pointer device. Table 2F-6 presents an example data form and Table 2F-7 is a look-up table with the recommended procedure. Procedures other than those recommended in Annex D in section 18 may be used, if they can determine R_{SLO} to within $\pm 1^\circ$ and are explained in detail in the field test report. The algebraic sign of R_{SLO} will either be positive, if the rotational position of the reference scribe line (as viewed from the "tail" end of the probe) is clockwise, or negative, if counterclockwise with respect to the probe's yaw-null position. (This is illustrated in Figure 2F-13.)

10.5.7 The steps in sections 10.5.3 through 10.5.6 shall be performed twice at each of the velocities at which the probe will be calibrated (in accordance with section 10.6). Record the values of R_{SLO} .

10.5.8 The average of all of the R_{SLO} values shall be documented as the reference scribe line rotational offset for the probe.

10.5.9 Use of reference scribe line offset. The reference scribe line rotational offset shall be used to determine the yaw angle of flow in accordance with section 8.9.4.

10.6 Pitch Angle and Velocity Pressure Calibrations. Use the procedures in sections 10.6.1 through 10.6.16 to generate an appropriate set (or sets) of pitch angle and velocity pressure calibration curves for each probe. The calibration procedure shall be performed on the main probe and all devices that will be attached to the main probe in the field (e.g., thermocouple or RTDs) that may affect the flow around the probe head. Probe shaft extensions that do not affect

flow around the probe head need not be attached during calibration. (Note: If a sampling nozzle is part of the assembly, a wind tunnel demonstration shall be performed that shows the probe's ability to measure velocity and yaw null is not impaired when the nozzle is drawing a sample.) The calibration procedure involves generating two calibration curves, F_1 versus pitch angle and F_2 versus pitch angle. To generate these two curves, F_1 and F_2 shall be derived using Equations 2F-1 and 2F-2, below. Table 2F-8 provides an example wind tunnel calibration data sheet, used to log the measurements needed to derive these two calibration curves.

10.6.1 Calibration velocities. The tester may calibrate the probe at two nominal wind tunnel velocity settings of 18.3 m/sec and 27.4 m/sec (60 ft/sec and 90 ft/sec) and average the results of these calibrations, as described in section 10.6.16.1, in order to generate a set of calibration curves. If this option is selected, this single set of calibration curves may be used for all field applications over the entire velocity range allowed by the method. Alternatively, the tester may customize the probe calibration for a particular field test application (or for a series of applications), based on the expected average velocity(ies) at the test site(s). If this option is selected, generate each set of calibration curves by calibrating the probe at two nominal wind tunnel velocity settings, at least one of which is greater than or equal to the expected average velocity(ies) for the field application(s), and average the results as described in section 10.6.16.1. Whichever calibration option is selected, the probe calibration coefficients (F_2 values) obtained at the two nominal calibration velocities shall, for the same pitch angle setting, meet the conditions specified in section 10.6.16.

10.6.2 Pitch angle calibration curve (F_1 versus pitch angle). The pitch angle calibration involves generating a calibration curve of calculated F_1 values versus tested pitch angles, where F_1 is the ratio of the pitch pressure to the velocity pressure, i.e.,

$$F_1 = \frac{(P_4 - P_5)}{(P_1 - P_2)} \quad \text{Eq. 2F-1}$$

See Figure 2F-14 for an example F_1 versus pitch angle calibration curve.

10.6.3 Velocity calibration curve (F_2 versus pitch angle). The velocity calibration involves generating a calibration curve of the 3-D probe's F_2 coefficient against the tested pitch angles, where

$$F_2 = C_p \sqrt{\frac{\Delta P_{std}}{(P_1 - P_2)}} \quad \text{Eq. 2F-2}$$

and

C_p = calibration pitot tube coefficient, and

ΔP_{std} = velocity pressure from the calibration pitot tube.

See Figure 2F–15 for an example F_2 versus pitch angle calibration curve.

10.6.4 Connect the tested probe and calibration pitot probe to their respective pressure-measuring devices. Zero the pressure-measuring devices. Inspect and leak-check all pitot lines; repair or replace, if necessary. Turn on the fan, and allow the wind tunnel air flow to stabilize at the first of the two selected nominal velocity settings.

10.6.5 Position the calibration pitot tube at its measurement location (determined as outlined in section 6.11.4.3), and align the tube so that its tip is pointed directly into the flow. Ensure that the entry port surrounding the tube is properly sealed. The calibration pitot tube may either remain in the wind tunnel throughout the calibration, or be removed from the wind tunnel while measurements are taken with the probe being calibrated.

10.6.6 Set up the pitch protractor plate on the tested probe's entry port to establish the pitch angle positions of the probe to within $\pm 2^\circ$.

10.6.7 Check the zero setting of each pressure-measuring device.

10.6.8 Insert the tested probe into the wind tunnel and align it so that its P_1 pressure port is pointed directly into the flow and is positioned within the calibration location (as defined in section 3.20). Secure the probe at the 0° pitch angle position. Ensure that the entry port surrounding the probe is properly sealed.

10.6.9 Read the differential pressure from the calibration pitot tube (ΔP_{std}), and record its value. Read the barometric pressure to within ± 2.5 mm Hg (± 0.1 in. Hg) and the temperature in the wind tunnel to within 0.6°C (1°F). Record these values on a data form similar to Table 2F–8.

10.6.10 After the tested probe's differential pressure gauges have had sufficient time to stabilize, yaw null the probe, then obtain differential pressure readings for (P_1 – P_2) and (P_4 – P_5). Record the yaw angle and differential pressure readings. After taking these readings, ensure that the tested probe has remained at the yaw-null position.

10.6.11 Either take paired differential pressure measurements with both the calibration pitot tube and tested probe (according to sections 10.6.9 and 10.6.10) or take readings only with the tested probe (according to section 10.6.10) in 5° increments over the pitch-angle range for which the probe is to be calibrated. The calibration pitch-angle range shall be symmetric around 0° and shall exceed the largest pitch angle expected in the field by 5° . At a minimum, probes shall be calibrated over the range of -15° to $+15^\circ$. If paired calibration pitot tube and tested probe measurements are not taken at each pitch angle setting, the differential pressure from the calibration pitot tube shall be read, at a minimum, before taking the tested probe's differential pressure reading at the first pitch angle setting and after taking the tested probe's differential pressure readings at the last pitch angle setting in each replicate.

10.6.12 Perform a second replicate of the procedures in sections 10.6.5 through 10.6.11 at the same nominal velocity setting.

10.6.13 For each replicate, calculate the F_1 and F_2 values at each pitch angle. At each pitch angle, calculate the percent difference between the two F_2 values using Equation 2F-3.

$$\%Diff = \frac{F_2^{\max} - F_2^{\min}}{F_2^{\min}} \times 100\% \quad Eq. 2F-3$$

If the percent difference is less than or equal to 2 percent, calculate an average F_1 value and an average F_2 value at that pitch angle. If the percent difference is greater than 2 percent and less than or equal to 5 percent, perform a third repetition at that angle and calculate an average F_1 value and an average F_2 value using all three repetitions. If the percent difference is greater than 5 percent, perform four additional repetitions at that angle and calculate an average F_1 value and an average F_2 value using all six repetitions. When additional repetitions are required at any pitch angle, move the probe by at least 5° and then return to the specified pitch angle before taking the next measurement. Record the average values on a form similar to Table 2F-9.

10.6.14 Repeat the calibration procedures in sections 10.6.5 through 10.6.13 at the second selected nominal wind tunnel velocity setting.

10.6.15 Velocity drift check. The following check shall be performed, except when paired calibration pitot tube and tested probe pressure measurements are taken at each pitch angle setting. At each velocity setting, calculate the percent difference between consecutive differential pressure measurements made with the calibration pitot tube. If a measurement differs from the previous measurement by more than 2 percent or 0.25 mm H₂O (0.01 in. H₂O), whichever is less restrictive, the calibration data collected between these calibration pitot tube measurements may not be used, and the measurements shall be repeated.

10.6.16 Compare the averaged F_2 coefficients obtained from the calibrations at the two selected nominal velocities, as follows. At each pitch angle setting, use Equation 2F-3 to calculate the difference between the corresponding average F_2 values at the two calibration velocities. At each pitch angle in the -15° to $+15^\circ$ range, the percent difference between the average F_2 values shall not exceed 3.0 percent. For pitch angles outside this range (i.e., less than -15° and greater than $+15^\circ$), the percent difference shall not exceed 5.0 percent.

10.6.16.1 If the applicable specification in section 10.6.16 is met at each pitch angle setting, average the results obtained at the two nominal calibration velocities to produce a calibration record of F_1 and F_2 at each pitch angle tested. Record these values on a form similar to Table 2F-9. From these values, generate one calibration curve representing F_1 versus pitch angle and a second curve representing F_2 versus pitch angle. Computer spreadsheet programs may be used to graph the calibration data and to develop polynomial equations that can be used to calculate pitch angles and axial velocities.

10.6.16.2 If the applicable specification in section 10.6.16 is exceeded at any pitch angle setting, the probe shall not be used unless: (1) the calibration is repeated at that pitch angle and acceptable results are obtained or (2) values of F_1 and F_2 are obtained at two nominal velocities for which the specifications in section 10.6.16 are met across the entire pitch angle range.

10.7 Recalibration. Recalibrate the probe using the procedures in section 10 either within 12 months of its first field use after its most recent calibration or after 10 field tests (as defined in section 3.4), whichever occurs later. In addition, whenever there is visible damage to the 3-D head, the probe shall be recalibrated before it is used again.

10.8 Calibration of pressure-measuring devices used in field tests. Before its initial use in a field test, calibrate each pressure-measuring device (except those used exclusively for yaw nulling) using the three-point calibration procedure described in section 10.3.3. The device shall be recalibrated according to the procedure in section 10.3.3 no later than 90 days after its first field use following its most recent calibration. At the discretion of the tester, more frequent calibrations (e.g., after a field test) may be performed. No adjustments, other than adjustments to the zero setting, shall be made to the device between calibrations.

10.8.1 Post-test calibration check. A single-point calibration check shall be performed on each pressure-measuring device after completion of each field test. At the discretion of the tester, more frequent single-point calibration checks (e.g., after one or more field test runs) may be performed. It is recommended that the post-test check be performed before leaving the field test site. The check shall be performed at a pressure between 50 and 90 percent of full scale by taking a common pressure reading with the tested device and a reference pressure-measuring device (as described in section 6.4.4) or by challenging the tested device with a reference pressure source (as described in section 6.4.4) or by performing an equivalent check using a reference device approved by the Administrator.

10.8.2 Acceptance criterion. At the selected pressure setting, the pressure readings made using the reference device and the tested device shall agree to within 3 percent of full scale of the tested device or 0.8 mm H₂O (0.03 in. H₂O), whichever is less restrictive. If this specification is met, the test data collected during the field test are valid. If the specification is not met, all test data collected since the last successful calibration or calibration check are invalid and shall be repeated using a pressure-measuring device with a current, valid calibration. Any device that fails the calibration check shall not be used in a field test until a successful recalibration is performed according to the procedures in section 10.3.3.

10.9 Temperature Gauges. Same as Method 2, section 4.3. The alternative thermocouple calibration procedures outlined in Emission Measurement Center (EMC) Approved Alternative Method (ALT-011) "Alternative Method 2 Thermocouple Calibration Procedure" may be performed. Temperature gauges shall be calibrated no more than 30 days prior to the start of a field test or series of field tests and recalibrated no more than 30 days after completion of a field test or series of field tests.

10.10 Barometer. Same as Method 2, section 4.4. The barometer shall be calibrated no more than 30 days prior to the start of a field test or series of field tests.

11.0 Analytical Procedure

Sample collection and analysis are concurrent for this method (see section 8.0).

12.0 Data Analysis and Calculations

These calculations use the measured yaw angle, derived pitch angle, and the differential pressure and temperature measurements at individual traverse points to derive the axial flue gas velocity ($v_a(i)$) at each of those points. The axial velocity values at all traverse points that comprise a full stack or duct traverse are then averaged to obtain the average axial flue gas velocity ($v_a(\text{avg})$). Round off figures only in the final calculation of reported values.

12.1 Nomenclature

A = Cross-sectional area of stack or duct, m^2 (ft^2).

B_{ws} = Water vapor in the gas stream (from Method 4 or alternative), proportion by volume.

K_p Conversion factor (a constant),

$$34.97 \frac{m}{\text{sec}} \left[\frac{(g/g\text{-mole})(mm\text{ Hg})}{(^{\circ}K)(mm\text{ H}_2\text{O})} \right]^{1/2}$$

for the metric system, and

$$85.49 \frac{ft}{\text{sec}} \left[\frac{(lb/lb\text{-mole})(in.\text{ Hg})}{(^{\circ}R)(in.\text{ H}_2\text{O})} \right]^{1/2}$$

for the English system.

M_d = Molecular weight of stack or duct gas, dry basis (see section 8.13), g/g-mole (lb/lb-mole).

M_s = Molecular weight of stack or duct gas, wet basis, g/g-mole (lb/lb-mole).

$$M_s = M_d(1 - B_{ws}) + 18.0B_{ws} \quad \text{Eq. 2F-4}$$

P_{bar} = Barometric pressure at measurement site, mm Hg (in. Hg).

P_g = Stack or duct static pressure, mm H₂O (in. H₂O).

P_s = Absolute stack or duct pressure, mm Hg (in. Hg),

$$P_s = P_{\text{bar}} + \frac{P_g}{13.6} \quad \text{Eq. 2F-5}$$

P_{std} = Standard absolute pressure, 760 mm Hg (29.92 in. Hg).

13.6 = Conversion from mm H₂O (in. H₂O) to mm Hg (in. Hg).

Q_{sd} = Average dry-basis volumetric stack or duct gas flow rate corrected to standard conditions, dscm/hr (dscf/hr).

Q_{sw} = Average wet-basis volumetric stack or duct gas flow rate corrected to standard conditions, wscm/hr (wscf/hr).

$Ts(avg)$ = Average absolute stack or duct gas temperature across all traverse points.

$ts(i)$ = Stack or duct gas temperature, C (F), at traverse point i.

$Ts(i)$ = Absolute stack or duct gas temperature, K (R), at traverse point i,

$$T_{s(i)} = 273 + t_{s(i)} \quad \text{Eq. 2F-6}$$

for the metric system, and

$$T_{s(i)} = 460 + t_{s(i)} \quad \text{Eq. 2F-7}$$

for the English system.

T_{std} = Standard absolute temperature, 293°K (528°R).

$F_{1(i)}$ = Pitch angle ratio, applicable at traverse point i, dimensionless.

$F_{2(i)}$ = 3-D probe velocity calibration coefficient, applicable at traverse point i, dimensionless.

$(P_4 - P_5)_i$ = Pitch differential pressure of stack or duct gas flow, mm H₂O (in. H₂O), at traverse point i.

$(P_1 - P_2)_i$ = Velocity head (differential pressure) of stack or duct gas flow, mm H₂O (in. H₂O), at traverse point i.

$va(i)$ = Reported stack or duct gas axial velocity, m/sec (ft/sec), at traverse point i.

$va(avg)$ = Average stack or duct gas axial velocity, m/sec (ft/sec), across all traverse points.

3,600 = Conversion factor, sec/hr.

18.0 = Molecular weight of water, g/g-mole (lb/lb-mole).

$\theta y(i)$ = Yaw angle, degrees, at traverse point i.

$\theta_p(i)$ = Pitch angle, degrees, at traverse point i .

n = Number of traverse points.

12.2 Traverse Point Velocity Calculations. Perform the following calculations from the measurements obtained at each traverse point.

12.2.1 Selection of calibration curves. Select calibration curves as described in section 10.6.1.

12.2.2 Traverse point pitch angle ratio. Use Equation 2F-1, as described in section 10.6.2, to calculate the pitch angle ratio, $F_{1(i)}$, at each traverse point.

12.2.3 Pitch angle. Use the pitch angle ratio, $F_{1(i)}$, to derive the pitch angle, $\theta_p(i)$, at traverse point i from the F_1 versus pitch angle calibration curve generated under section 10.6.16.1.

12.2.4 Velocity calibration coefficient. Use the pitch angle, $\theta_p(i)$, to obtain the probe velocity calibration coefficient, $F_{2(i)}$, at traverse point i from the “velocity pressure calibration curve,” i.e., the F_2 versus pitch angle calibration curve generated under section 10.6.16.1.

12.2.5 Axial velocity. Use the following equation to calculate the axial velocity, $v_a(i)$, from the differential pressure $(P_1 - P_2)_i$ and yaw angle, $\theta_y(i)$, measured at traverse point i and the previously calculated values for the velocity calibration coefficient, $F_{2(i)}$, absolute stack or duct standard temperature, $T_s(i)$, absolute stack or duct pressure, P_s , molecular weight, M_s , and pitch angle, “ $\theta_p(i)$.”

$$v_{a(i)} = K_p F_{2(i)} \sqrt{\frac{(P_1 - P_2)_i T_s(i)}{P_s M_s}} (\cos \theta_{y(i)}) (\cos \theta_{p(i)}) \quad \text{Eq. 2F-8}$$

12.2.6 Handling multiple measurements at a traverse point. For pressure or temperature devices that take multiple measurements at a traverse point, the multiple measurements (or where applicable, their square roots) may first be averaged and the resulting average values used in the equations above. Alternatively, the individual measurements may be used in the equations above and the resulting multiple calculated values may then be averaged to obtain a single traverse point value. With either approach, all of the individual measurements recorded at a traverse point must be used in calculating the applicable traverse point value.

12.3 Average Axial Velocity in Stack or Duct. Use the reported traverse point axial velocity in the following equation.

$$v_{a(avg)} = \frac{\sum_{i=1}^n v_{a(i)}}{n} \quad \text{Eq. 2F-9}$$

12.4 Acceptability of Results. The test results are acceptable and the calculated value of $v_{a(avg)}$ may be reported as the average axial velocity for the test run if the conditions in either section 12.4.1 or 12.4.2 are met.

12.4.1 The calibration curves were generated at nominal velocities of 18.3 m/sec and 27.4 m/sec (60 ft/sec and 90 ft/sec).

12.4.2 The calibration curves were generated at nominal velocities other than 18.3 m/sec and 27.4 m/sec (60 ft/sec and 90 ft/sec), and the value of $v_{a(avg)}$ obtained using Equation 2F-9 is less than or equal to at least one of the nominal velocities used to derive the F_1 and F_2 calibration curves.

12.4.3 If the conditions in neither section 12.4.1 nor section 12.4.2 are met, the test results obtained in Equation 2F-9 are not acceptable, and the steps in sections 12.2 and 12.3 must be repeated using a set of F_1 and F_2 calibration curves that satisfies the conditions specified in section 12.4.1 or 12.4.2.

12.5 Average Gas Wet Volumetric Flow Rate in Stack or Duct. Use the following equation to compute the average volumetric flow rate on a wet basis.

$$Q_{sw} = 3,600(v_{a(avg)})(A)\left(\frac{T_{std}}{T_{s(avg)}}\right)\left(\frac{P_s}{P_{std}}\right) \quad \text{Eq. 2F-10}$$

12.6 Average Gas Dry Volumetric Flow Rate in Stack or Duct. Use the following equation to compute the average volumetric flow rate on a dry basis.

$$Q_{sd} = 3,600(1 - B_{ws})(v_{a(avg)})(A)\left(\frac{T_{std}}{T_{s(avg)}}\right)\left(\frac{P_s}{P_{std}}\right) \quad \text{Eq. 2F-11}$$

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 applicable regulatory requirements. Field test reports should, at a minimum, include the following elements.

16.1.1 Description of the source. This should include the name and location of the test site, descriptions of the process tested, a description of the combustion source, an accurate diagram of stack or duct cross-sectional area at the test site showing the dimensions of the stack or duct, the

location of the test ports, and traverse point locations and identification numbers or codes. It should also include a description and diagram of the stack or duct layout, showing the distance of the test location from the nearest upstream and downstream disturbances and all structural elements (including breachings, baffles, fans, straighteners, etc.) affecting the flow pattern. If the source and test location descriptions have been previously submitted to the Agency in a document (e.g., a monitoring plan or test plan), referencing the document in lieu of including this information in the field test report is acceptable.

16.1.2 Field test procedures. These should include a description of test equipment and test procedures. Testing conventions, such as traverse point numbering and measurement sequence (e.g., sampling from center to wall, or wall to center), should be clearly stated. Test port identification and directional reference for each test port should be included on the appropriate field test data sheets.

16.1.3 Field test data.

16.1.3.1 Summary of results. This summary should include the dates and times of testing and the average axial gas velocity and the average flue gas volumetric flow results for each run and tested condition.

16.1.3.2 Test data. The following values for each traverse point should be recorded and reported:

- (a) P_1 - P_2 and P_4 - P_5 differential pressures
- (b) Stack or duct gas temperature at traverse point i ($t_s(i)$)
- (c) Absolute stack or duct gas temperature at traverse point i ($T_s(i)$)
- (d) Yaw angle at each traverse point i ($\theta_y(i)$)
- (e) Pitch angle at each traverse point i ($\theta_p(i)$)
- (f) Stack or duct gas axial velocity at traverse point i ($v_a(i)$)

16.1.3.3 The following values should be reported once per run:

- (a) Water vapor in the gas stream (from Method 4 or alternative), proportion by volume (B_{ws}), measured at the frequency specified in the applicable regulation
- (b) Molecular weight of stack or duct gas, dry basis (M_d)
- (c) Molecular weight of stack or duct gas, wet basis (M_s)
- (d) Stack or duct static pressure (P_g)

- (e) Absolute stack or duct pressure (P_s)
- (f) Carbon dioxide concentration in the flue gas, dry basis ($0/0_d\text{CO}_2$)
- (g) Oxygen concentration in the flue gas, dry basis ($0/0_d\text{O}_2$)
- (h) Average axial stack or duct gas velocity ($v_{a(\text{avg})}$) across all traverse points
- (i) Gas volumetric flow rate corrected to standard conditions, dry or wet basis as required by the applicable regulation (Q_{sd} or Q_{sw})

16.1.3.4 The following should be reported once per complete set of test runs:

- (a) Cross-sectional area of stack or duct at the test location (A)
- (b) Measurement system response time (sec)
- (c) Barometric pressure at measurement site (P_{bar})

16.1.4 Calibration data. The field test report should include calibration data for all probes and test equipment used in the field test. At a minimum, the probe calibration data reported to the Agency should include the following:

- (a) Date of calibration
- (b) Probe type
- (c) Probe identification number(s) or code(s)
- (d) Probe inspection sheets
- (e) Pressure measurements and intermediate calculations of F_1 and F_2 at each pitch angle used to obtain calibration curves in accordance with section 10.6 of this method
- (f) Calibration curves (in graphic or equation format) obtained in accordance with sections 10.6.11 of this method
- (g) Description and diagram of wind tunnel used for the calibration, including dimensions of cross-sectional area and position and size of the test section
- (h) Documentation of wind tunnel qualification tests performed in accordance with section 10.1 of this method

16.1.5 Quality Assurance. Specific quality assurance and quality control procedures used during the test should be described.

17.0 Bibliography

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- (4) 40 CFR Part 60, Appendix A, Method 3—Gas analysis for carbon dioxide, oxygen, excess air, and dry molecular weight.
- (5) 40 CFR Part 60, Appendix A, Method 3A—Determination of oxygen and carbon dioxide concentrations in emissions from stationary sources (instrumental analyzer procedure).
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18.0 Annexes

Annex A, C, and D describe recommended procedures for meeting certain provisions in sections 8.3, 10.4, and 10.5 of this method. Annex B describes procedures to be followed when using the protractor wheel and pointer assembly to measure yaw angles, as provided under section 8.9.1.

18.1 Annex A—Rotational Position Check. The following are recommended procedures that may be used to satisfy the rotational position check requirements of section 8.3 of this method and to determine the angle-measuring device rotational offset R_{ADO} .

18.1.1 Rotational position check with probe outside stack. Where physical constraints at the sampling location allow full assembly of the probe outside the stack and insertion into the test port, the following procedures should be performed before the start of testing. Two angle-measuring devices that meet the specifications in section 6.2.1 or 6.2.3 are required for the rotational position check. An angle measuring device whose position can be independently adjusted (e.g., by means of a set screw) after being locked into position on the probe sheath shall not be used for this check unless the independent adjustment is set so that the device performs exactly like a device without the capability for independent adjustment. That is, when aligned on the probe such a device must give the same reading as a device that does not have the capability of being independently adjusted. With the fully assembled probe (including probe shaft extensions, if any) secured in a horizontal position, affix one yaw angle-measuring device to the probe sheath and lock it into position on the reference scribe line specified in section 6.1.6.1. Position the second angle-measuring device using the procedure in section 18.1.1.1 or 18.1.1.2.

18.1.1.1 Marking procedure. The procedures in this section should be performed at each location on the fully assembled probe where the yaw angle-measuring device will be mounted during the velocity traverse. Place the second yaw angle-measuring device on the main probe sheath (or extension) at the position where a yaw angle will be measured during the velocity traverse. Adjust the position of the second angle-measuring device until it indicates the same angle ($\pm 1^\circ$) as the reference device, and affix the second device to the probe sheath (or extension). Record the angles indicated by the two angle-measuring devices on a form similar to Table 2F-2. In this position, the second angle-measuring device is considered to be properly positioned for yaw angle measurement. Make a mark, no wider than 1.6 mm (1/16 in.), on the probe sheath (or extension), such that the yaw angle-measuring device can be re-affixed at this same properly aligned position during the velocity traverse.

18.1.1.2 Procedure for probe extensions with scribe lines. If, during a velocity traverse the angle-measuring device will be affixed to a probe extension having a scribe line as specified in section 6.1.6.2, the following procedure may be used to align the extension's scribe line with the reference scribe line instead of marking the extension as described in section 18.1.1.1. Attach the probe extension to the main probe. Align and lock the second angle-measuring device on the probe extension's scribe line. Then, rotate the extension until both measuring devices indicate the same angle ($\pm 1^\circ$). Lock the extension at this rotational position. Record the angles indicated by the two angle-measuring devices on a form similar to Table 2F-2. An angle-measuring device may be aligned at any position on this scribe line during the velocity traverse, if the scribe line meets the alignment specification in section 6.1.6.3.

18.1.1.3 Post-test rotational position check. If the fully assembled probe includes one or more extensions, the following check should be performed immediately after the completion of a velocity traverse. At the discretion of the tester, additional checks may be conducted after completion of testing at any sample port. Without altering the alignment of any of the components of the probe assembly used in the velocity traverse, secure the fully assembled probe

in a horizontal position. Affix an angle-measuring device at the reference scribe line specified in section 6.1.6.1. Use the other angle-measuring device to check the angle at each location where the device was checked prior to testing. Record the readings from the two angle-measuring devices.

18.1.2 Rotational position check with probe in stack. This section applies only to probes that, due to physical constraints, cannot be inserted into the test port as fully assembled with all necessary extensions needed to reach the inner-most traverse point(s).

18.1.2.1 Perform the out-of-stack procedure in section 18.1.1 on the main probe and any attached extensions that will be initially inserted into the test port.

18.1.2.2 Use the following procedures to perform additional rotational position check(s) with the probe in the stack, each time a probe extension is added. Two angle-measuring devices are required. The first of these is the device that was used to measure yaw angles at the preceding traverse point, left in its properly aligned measurement position. The second angle-measuring device is positioned on the added probe extension. Use the applicable procedures in section 18.1.1.1 or 18.1.1.2 to align, adjust, lock, and mark (if necessary) the position of the second angle-measuring device to within $\pm 1^\circ$ of the first device. Record the readings of the two devices on a form similar to Table 2F-2.

18.1.2.3 The procedure in section 18.1.2.2 should be performed at the first port where measurements are taken. The procedure should be repeated each time a probe extension is re-attached at a subsequent port, unless the probe extensions are designed to be locked into a mechanically fixed rotational position (e.g., through use of interlocking grooves), which can be reproduced from port to port as specified in section 8.3.5.2.

18.2 Annex B—Angle Measurement Protocol for Protractor Wheel and Pointer Device. The following procedure shall be used when a protractor wheel and pointer assembly, such as the one described in section 6.2.2 and illustrated in Figure 2F-7 is used to measure the yaw angle of flow. With each move to a new traverse point, unlock, re-align, and re-lock the probe, angle-pointer collar, and protractor wheel to each other. At each such move, particular attention is required to ensure that the scribe line on the angle pointer collar is either aligned with the reference scribe line on the main probe sheath or is at the rotational offset position established under section 8.3.1. The procedure consists of the following steps.

18.2.1 Affix a protractor wheel to the entry port for the test probe in the stack or duct.

18.2.2 Orient the protractor wheel so that the 0° mark corresponds to the longitudinal axis of the stack or duct. For stacks, vertical ducts, or ports on the side of horizontal ducts, use a digital inclinometer meeting the specifications in section 6.2.1 to locate the 0° orientation. For ports on the top or bottom of horizontal ducts, identify the longitudinal axis at each test port and permanently mark the duct to indicate the 0° orientation. Once the protractor wheel is properly aligned, lock it into position on the test port.

18.2.3 Move the pointer assembly along the probe sheath to the position needed to take measurements at the first traverse point. Align the scribe line on the pointer collar with the reference scribe line or at the rotational offset position established under section 8.3.1. Maintaining this rotational alignment, lock the pointer device onto the probe sheath. Insert the probe into the entry port to the depth needed to take measurements at the first traverse point.

18.2.4 Perform the yaw angle determination as specified in sections 8.9.3 and 8.9.4 and record the angle as shown by the pointer on the protractor wheel. Then, take velocity pressure and temperature measurements in accordance with the procedure in section 8.9.5. Perform the alignment check described in section 8.9.6.

18.2.5 After taking velocity pressure measurements at that traverse point, unlock the probe from the collar and slide the probe through the collar to the depth needed to reach the next traverse point.

18.2.6 Align the scribe line on the pointer collar with the reference scribe line on the main probe or at the rotational offset position established under section 8.3.1. Lock the collar onto the probe.

18.2.7 Repeat the steps in sections 18.2.4 through 18.2.6 at the remaining traverse points accessed from the current stack or duct entry port.

18.2.8 After completing the measurement at the last traverse point accessed from a port, verify that the orientation of the protractor wheel on the test port has not changed over the course of the traverse at that port. For stacks, vertical ducts, or ports on the side of horizontal ducts, use a digital inclinometer meeting the specifications in section 6.2.1 to check the rotational position of the 0° mark on the protractor wheel. For ports on the top or bottom of horizontal ducts, observe the alignment of the angle wheel 0° mark relative to the permanent 0° mark on the duct at that test port. If these observed comparisons exceed $\pm 2^\circ$ of 0°, all angle and pressure measurements taken at that port since the protractor wheel was last locked into position on the port shall be repeated.

18.2.9 Move to the next stack or duct entry port and repeat the steps in sections 18.2.1 through 18.2.8.

18.3 Annex C—Guideline for Reference Scribe Line Placement. Use of the following guideline is recommended to satisfy the requirements of section 10.4 of this method. The rotational position of the reference scribe line should be either 90° or 180° from the probe's impact pressure port.

18.4 Annex D—Determination of Reference Scribe Line Rotational Offset. The following procedures are recommended for determining the magnitude and sign of a probe's reference scribe line rotational offset, R_{SLO} . Separate procedures are provided for two types of angle-measuring devices: digital inclinometers and protractor wheel and pointer assemblies.

18.4.1 Perform the following procedures on the main probe with all devices that will be attached to the main probe in the field [such as thermocouples or resistance temperature detectors

(RTDs)] that may affect the flow around the probe head. Probe shaft extensions that do not affect flow around the probe head need not be attached during calibration.

18.4.2 The procedures below assume that the wind tunnel duct used for probe calibration is horizontal and that the flow in the calibration wind tunnel is axial as determined by the axial flow verification check described in section 10.1.2. Angle-measuring devices are assumed to display angles in alternating 0° to 90° and 90° to 0° intervals. If angle-measuring devices with other readout conventions are used or if other calibration wind tunnel duct configurations are used, make the appropriate calculational corrections.

18.4.2.1 Position the angle-measuring device in accordance with one of the following procedures.

18.4.2.1.1 If using a digital inclinometer, affix the calibrated digital inclinometer to the probe. If the digital inclinometer can be independently adjusted after being locked into position on the probe sheath (e.g., by means of a set screw), the independent adjustment must be set so that the device performs exactly like a device without the capability for independent adjustment. That is, when aligned on the probe the device must give the same readings as a device that does not have the capability of being independently adjusted. Either align it directly on the reference scribe line or on a mark aligned with the scribe line determined according to the procedures in section 18.1.1.1. Maintaining this rotational alignment, lock the digital inclinometer onto the probe sheath.

18.4.2.1.2 If using a protractor wheel and pointer device, orient the protractor wheel on the test port so that the 0° mark is aligned with the longitudinal axis of the wind tunnel duct. Maintaining this alignment, lock the wheel into place on the wind tunnel test port. Align the scribe line on the pointer collar with the reference scribe line or with a mark aligned with the reference scribe line, as determined under section 18.1.1.1. Maintaining this rotational alignment, lock the pointer device onto the probe sheath.

18.4.2.2 Zero the pressure-measuring device used for yaw nulling.

18.4.2.3 Insert the probe assembly into the wind tunnel through the entry port, positioning the probe's impact port at the calibration location. Check the responsiveness of the pressure-measuring device to probe rotation, taking corrective action if the response is unacceptable.

18.4.2.4 Ensure that the probe is in a horizontal position using a carpenter's level.

18.4.2.5 Rotate the probe either clockwise or counterclockwise until a yaw null ($P_2=P_3$) is obtained.

18.4.2.6 Read and record the value of θ_{null} , the angle indicated by the angle-measuring device at the yaw-null position. Record the angle reading on a form similar to Table 2F-6. Do not associate an algebraic sign with this reading.

18.4.2.7 Determine the magnitude and algebraic sign of the reference scribe line rotational offset, R_{SLO} . The magnitude of R_{SLO} will be equal to either θ_{null} or $(90^\circ - \theta_{null})$, depending on the angle-measuring device used. (See Table 2F-7 for a summary.) The algebraic sign of R_{SLO} will either be positive, if the rotational position of the reference scribe line is clockwise, or negative, if counterclockwise with respect to the probe's yaw-null position. Figure 2F-13 illustrates how the magnitude and sign of R_{SLO} are determined.

18.4.2.8 Perform the steps in sections 18.4.2.3 through 18.4.2.7 twice at each of the two calibration velocities selected for the probe under section 10.6. Record the values of R_{SLO} in a form similar to Table 2F-6.

18.4.2.9 The average of all R_{SLO} values is the reference scribe line rotational offset for the probe.

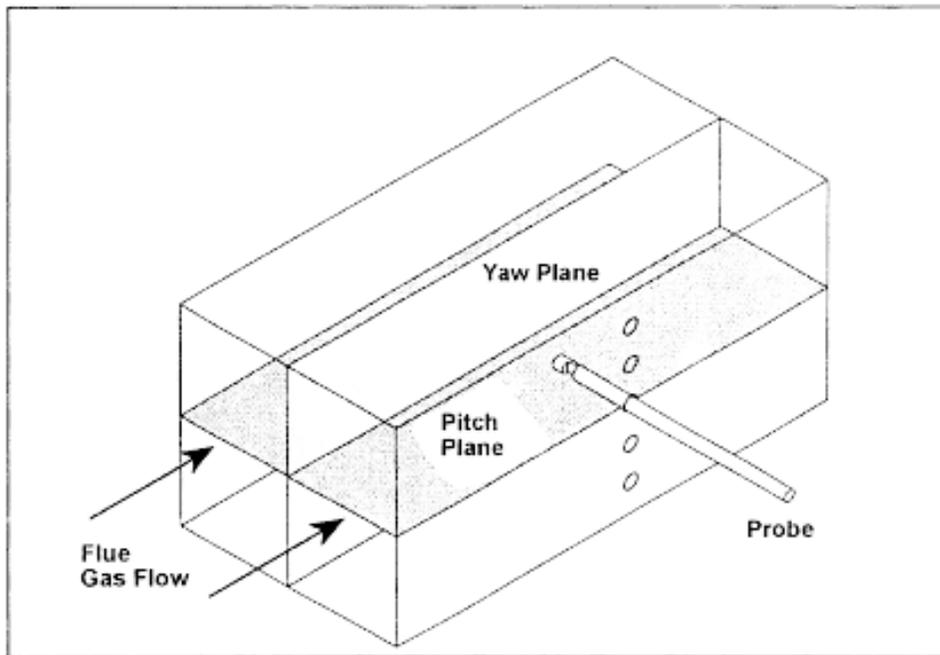


Figure 2F-1. Illustration of yaw and pitch planes in stack or duct.

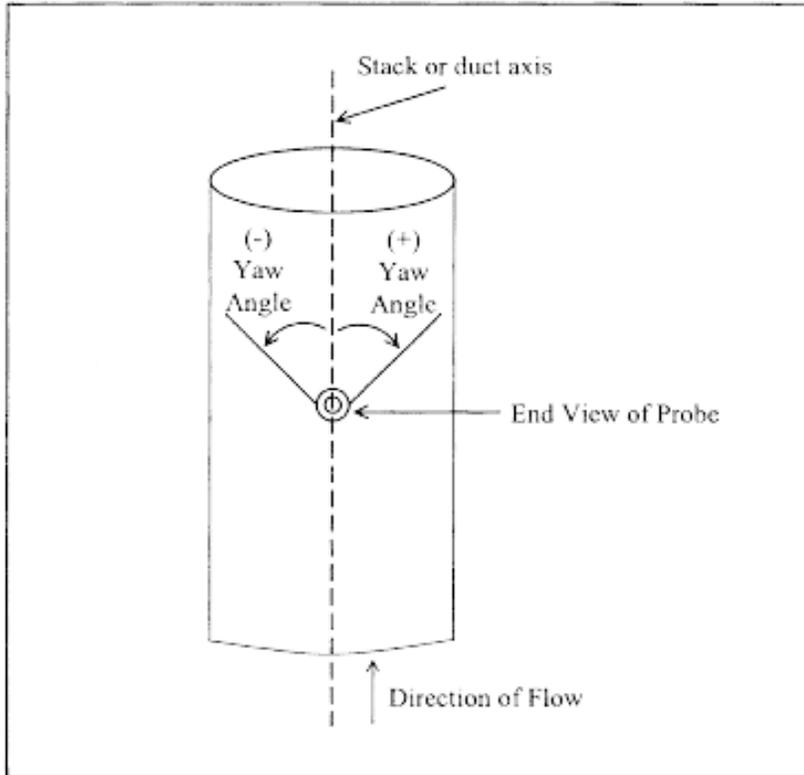


Figure 2F-2. Illustration of probe rotation representing positive and negative yaw angles.

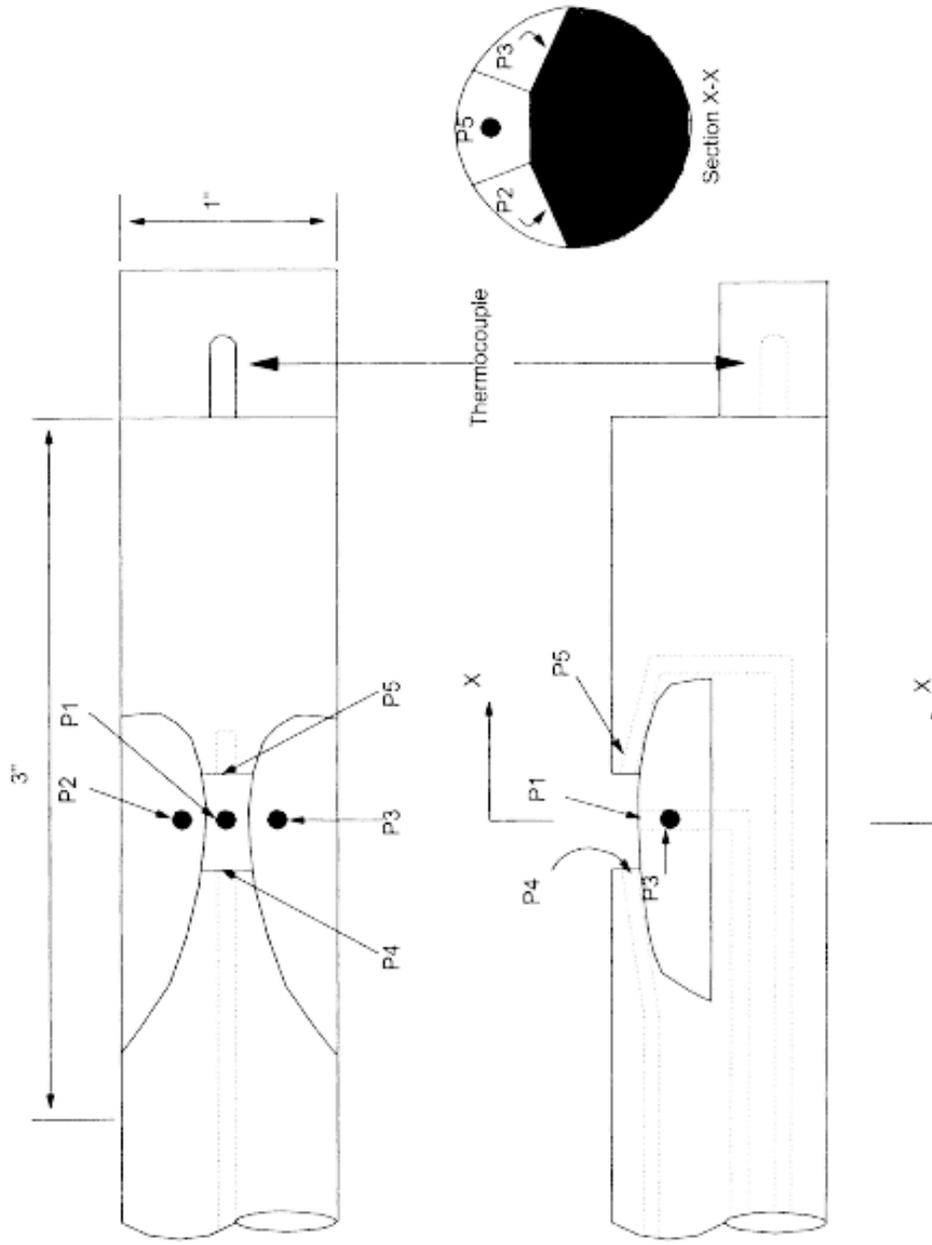


Figure 2F-3. Illustration of a five-hole prism-shaped (DAT) probe.

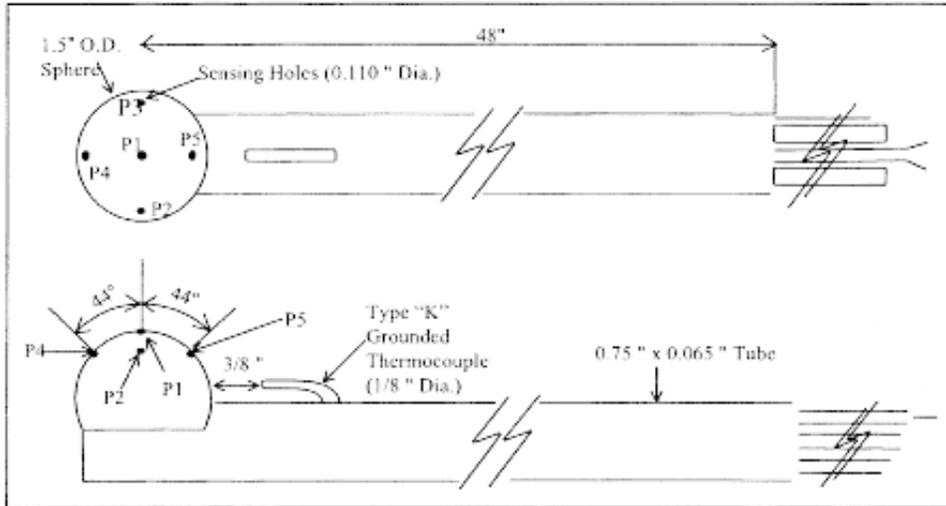


Figure 2F-4. Illustration of front and side view of spherical probe.

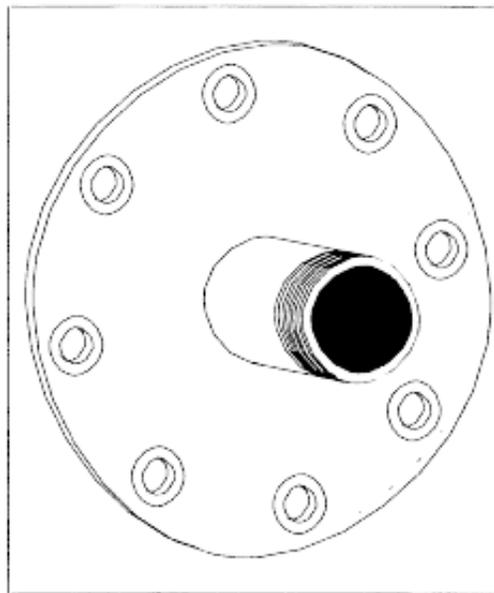


Figure 2F-5. Example bushing sleeve.

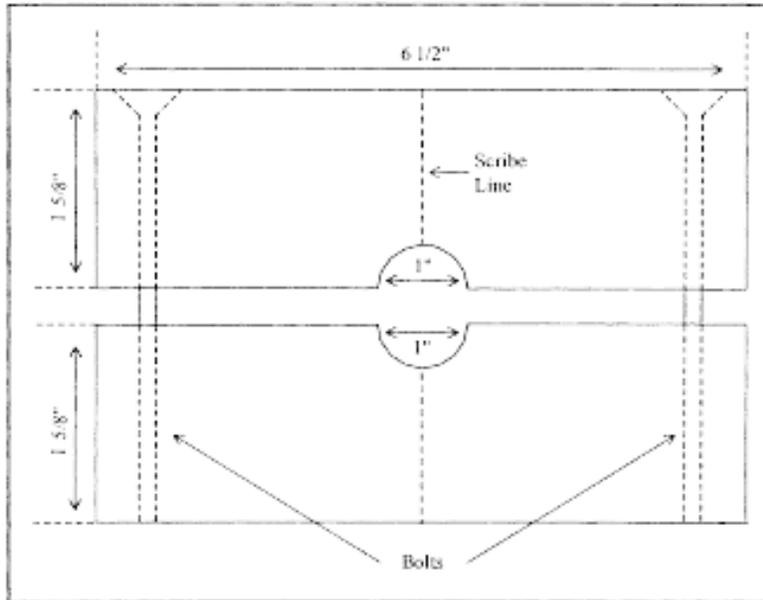


Figure 2F-6. Rotational position collar block.

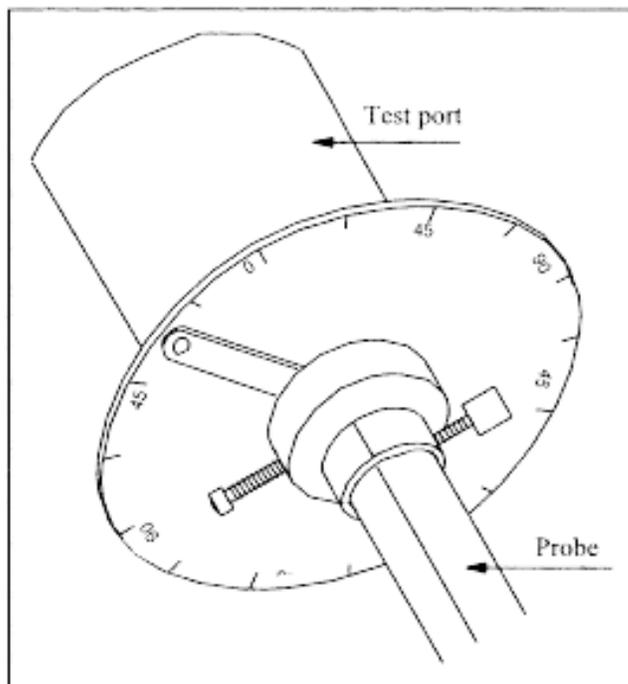


Figure 2F-7. Yaw angle protractor wheel and pointer.

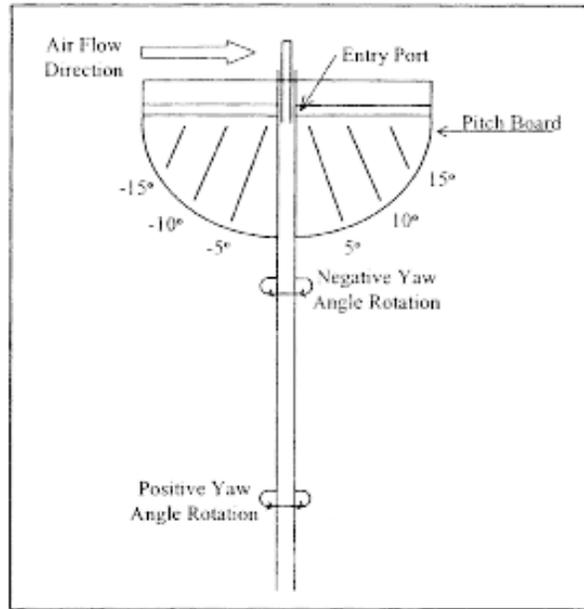


Figure 2F-8. Pitch angle protractor plate.

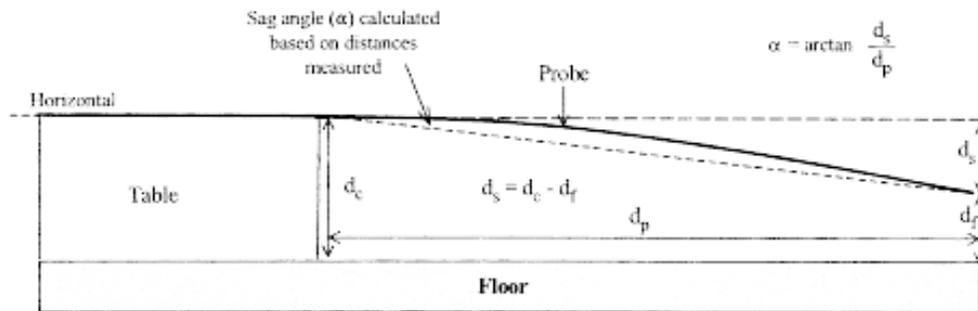


Figure 2F-9. Elements in horizontal straightness test using trigonometry.

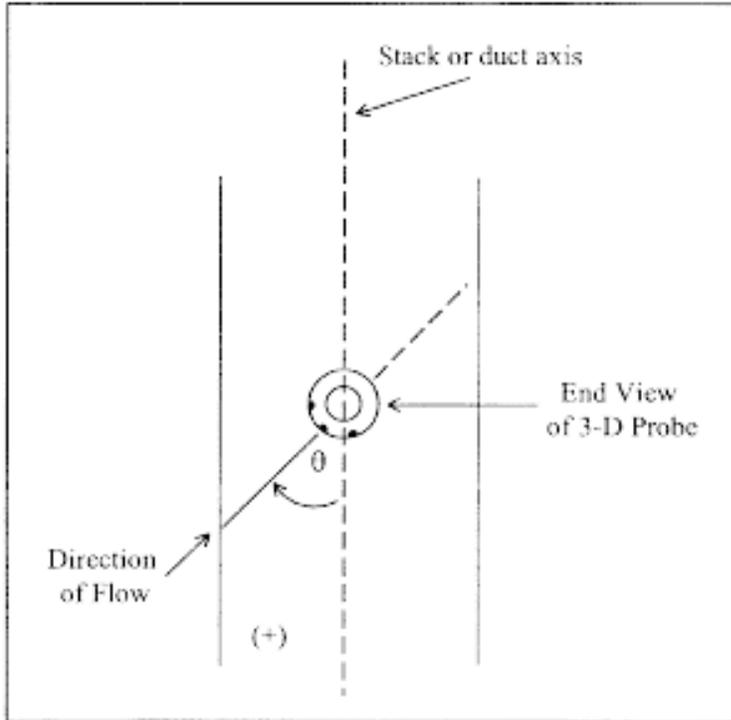


Figure 2F-10. Sign convention for the measured angle (θ) when the probe impact port is pointed directly into the flow. The angle θ is positive when the probe's impact pressure port is oriented in a clockwise rotational position relative to the stack or duct axis, as shown above and negative for a counterclockwise orientation.

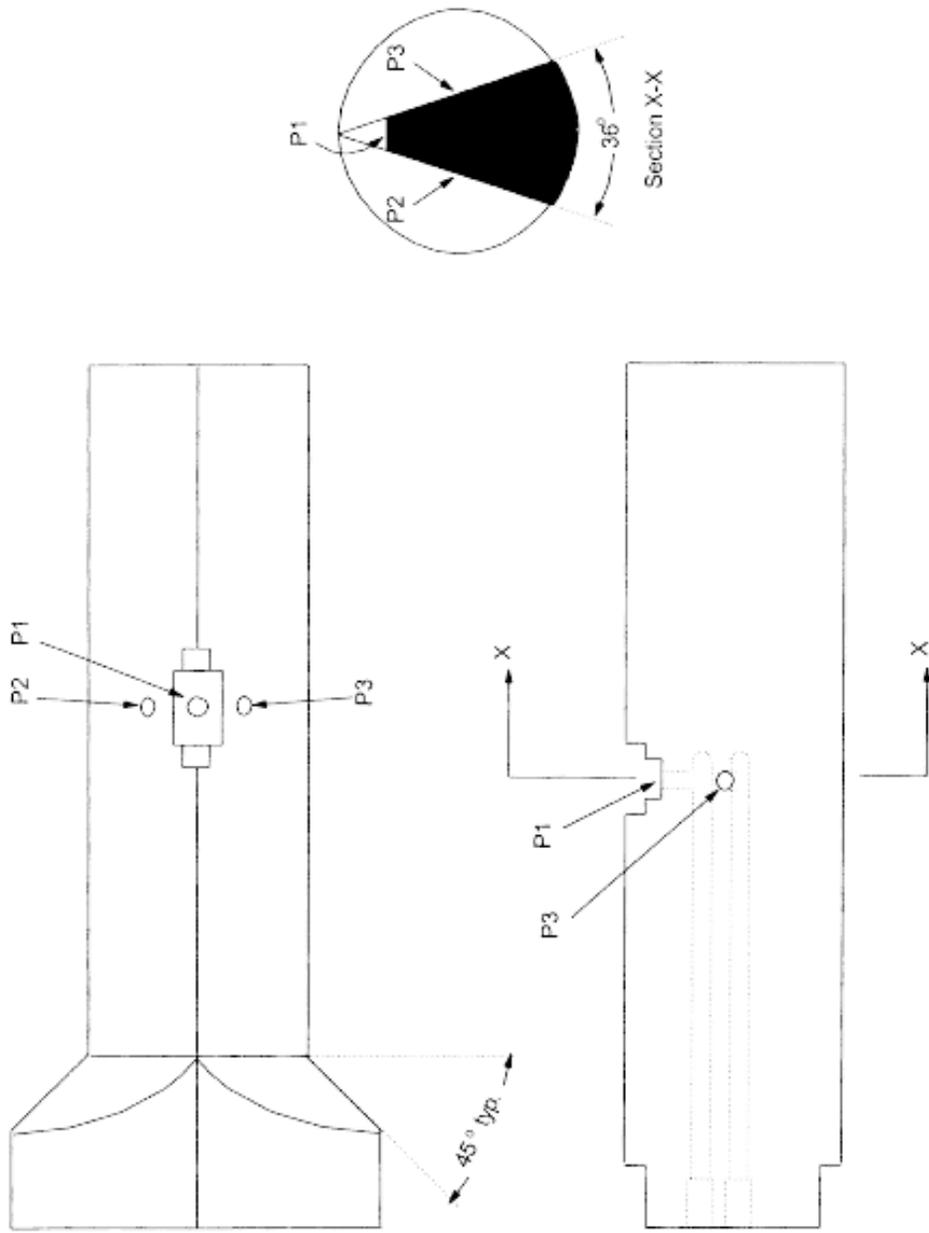


Figure 2F-11. Wedge probe used for axial flow verification.

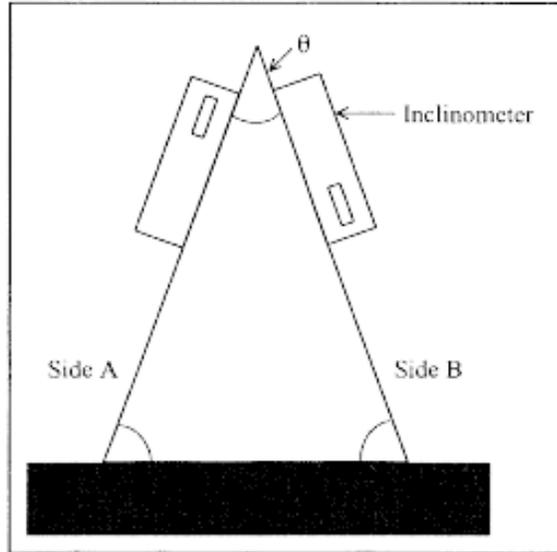


Figure 2F-12. Triangular block used for digital inclinometer calibration.

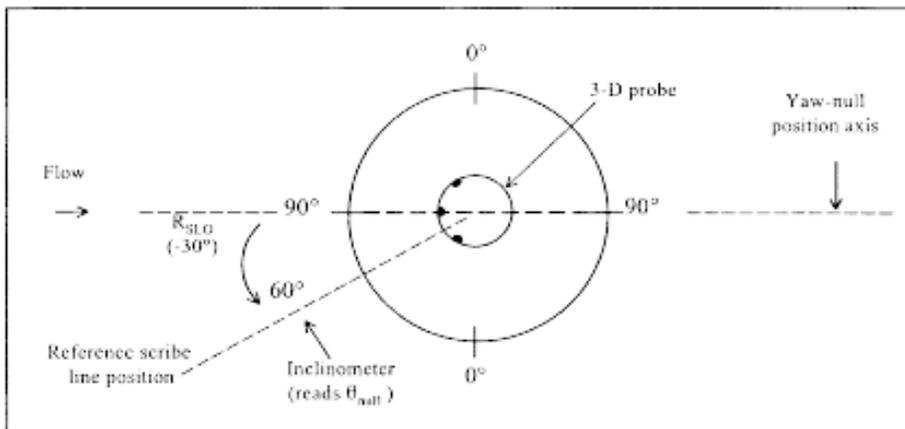


Figure 2F-13. Determination of reference scribe line rotational offset (R_{SLO}) in a horizontal wind tunnel with axial flow for a 3-D probe. The probe impact pressure port is aligned with the yaw-null position and is pointed into the flow. The inclinometer reads θ_{null} . The magnitude of $R_{SLO} = 90^\circ - \theta_{null}$ and the sign is a negative (counterclockwise from yaw-null position axis).

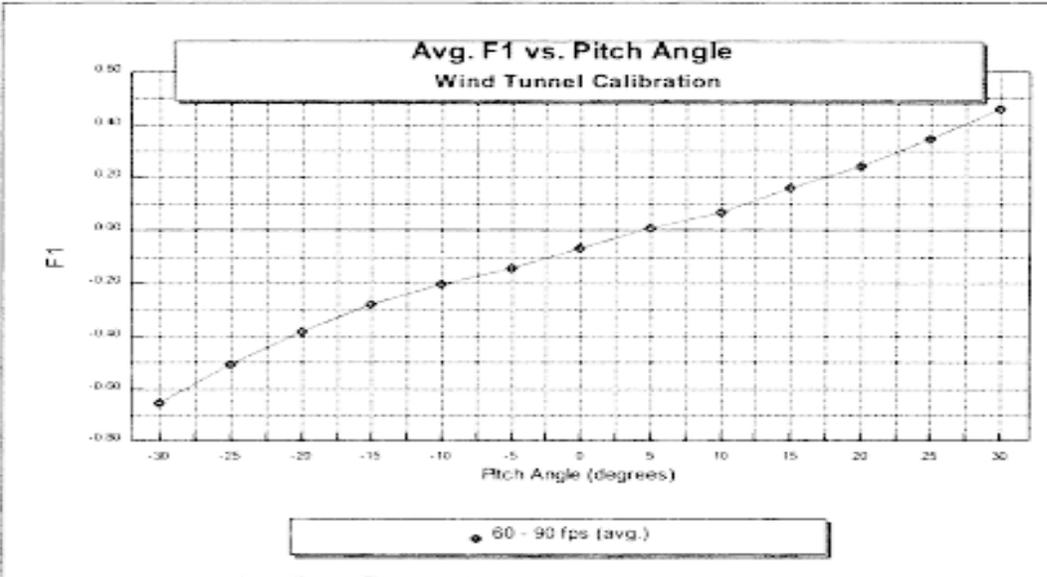


Figure 2F-14. Example F_1 calibration curve for the DAT probe.

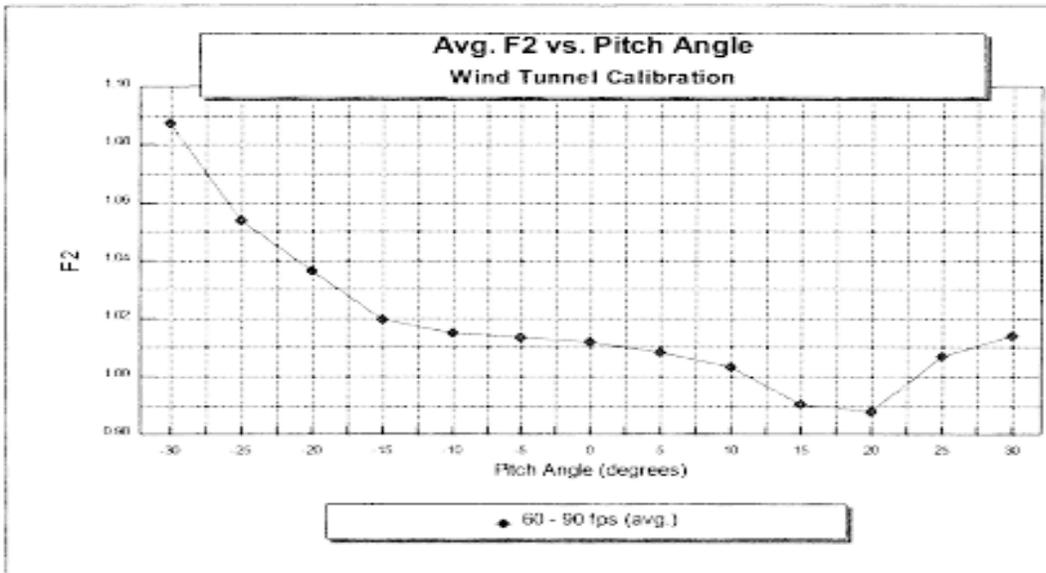


Figure 2F-15. Example F_2 calibration curve for the DAT probe.

Table 2F-1. 3-D Probe Inspection Sheet

Probe Type and ID # _____ **Date of most recent calibration:** _____

Fill in the tables below. For any item assigned a value of "1", show its location in the accompanying probe diagrams.

Inspection of Probe Ports

Port ID	Current Inspection (1=present, 0=absent)			Compared to Previous Calibration (1=changed, 0=unchanged)			Brief Description of Any Item with a Value of "1" in Preceding Columns
	Dents	Scratches	Asymmetries	Dents	Scratches	Asymmetries	
P1							
P2							
P3							
P4							
P5							

Inspection of Probe Surfaces

Surface ID	Current Inspection (1=present, 0=absent)		Compared to Previous Calibration (1=changed, 0=unchanged)		Brief Description of Any Item with a Value of "1" in Preceding Columns
	Scratches	Indentations	Scratches	Indentations	
S1					
S2					
S3					
S4					
S5					

Surface IDs S1 through S5 refer to the surfaces adjacent to pressure ports with the corresponding numbers, e.g., S3 refers to the surface adjacent to pressure port P3.

QA/QC Check

Completeness ___ Legibility ___ Accuracy ___ Specifications ___ Reasonableness ___

Certification

I certify that the Probe ID _____ meets or exceeds all specifications, criteria, and/or applicable design features required under Method 2F.

Certified by: _____ Date: _____

Table 2F-1. 3-D Probe Inspection Sheet (continued)

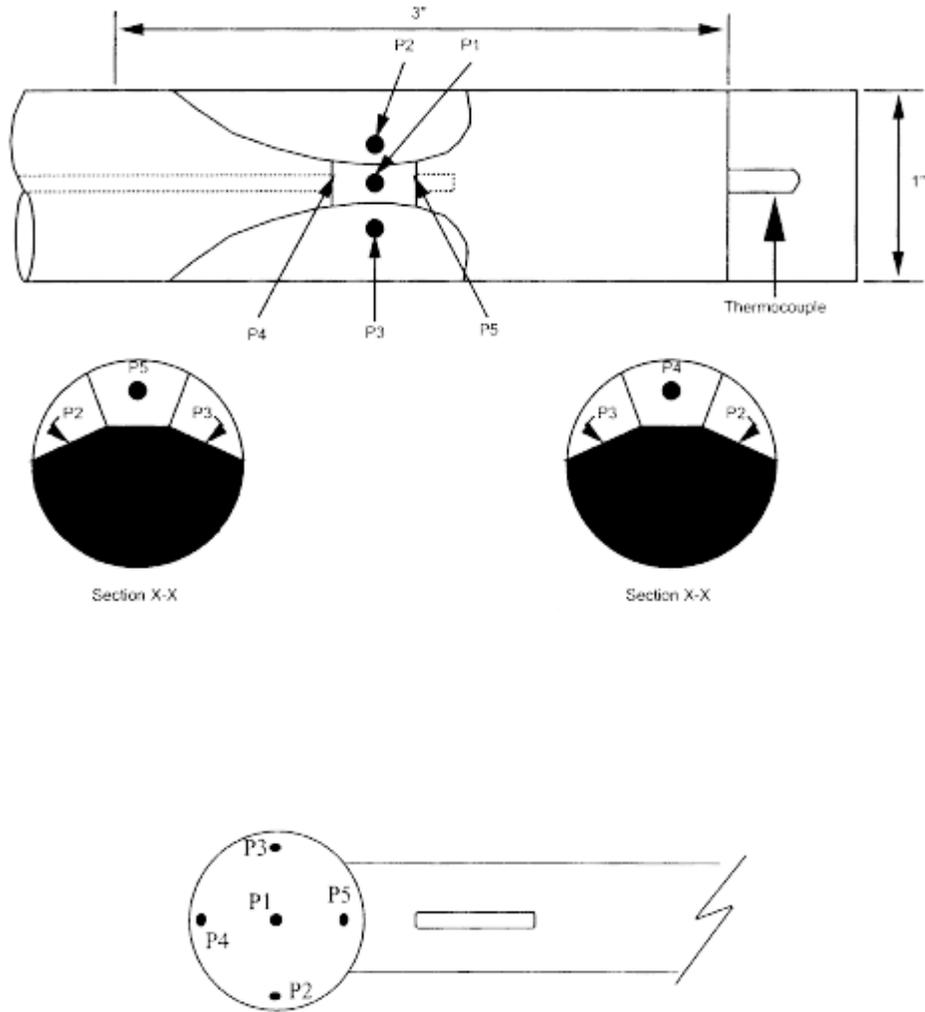


Table 2F-2. Rotational Position Check

Source: _____ Date: _____
 Test Location: _____ Tester(s): _____
 Probe Type: _____ Affiliation: _____
 Probe ID: _____ Fully-Assembled Probe Length (in.): _____

Position	Angle Comparisons		
Distance of 2 nd measurement device from probe head impact port in mm (in.)	1st Device Angle measured by device aligned on the reference scribe line, including algebraic sign (degrees)	2nd Device Angle measured by device mounted at each position to be used during testing, including algebraic sign (degrees)	R_{ADO} Difference between readings by 1 st and 2 nd angle-measuring devices (degrees) ^a
(Col. A)	(Col. B)	(Col. C)	(Col. C - Col. B)

^a The algebraic sign must be consistent with section 8.3.2.

Specifications: For the pre-test rotational position check, the value of R_{ADO} at each location along the probe shaft must be determined to within $\pm 1^\circ$. In the post-test check, R_{ADO} at each location must remain within $\pm 2^\circ$ of the value obtained in the pre-test check.

Table 2F-4. Wind Tunnel Velocity Pressure Cross-Check

Wind Tunnel Facility: _____
 Date: _____
 Wind Tunnel Temperature: _____
 Barometric Pressure: _____
 Test Point Locations: _____
 Lowest Test Velocity in m/sec (ft/sec): _____
 Highest Test Velocity in m/sec (ft/sec): _____

Port	Rep.	Velocity Pressure (ΔP_{vd})	
		@ Lowest Test Velocity	@ Highest Test Velocity
Calibration Pitot Tube Location	1		
	2		
	3		
	Average		
Calibration Location Test Points *	1	1	
		2	
		3	
		Average	
		% Difference **	
	2	1	
		2	
		3	
		Average	
		% Difference **	
		1	
		2	
		3	
		Average	
		% Difference **	

* Measurements must be taken at all points in the calibration location as specified in section 10.1.1

** Percent Difference =
$$\frac{(\text{Calibration Location Test Point Avg} - \text{Cal. Pitot Tube Location Avg})}{\text{Cal. Pitot Tube Location Avg}} \times 100\%$$

Specification: At each velocity setting, the average velocity pressure obtained at the calibration location shall be within ± 2 percent or 0.01 in. H₂O, whichever is less restrictive, of the average velocity pressure obtained at the fixed calibration pitot tube location.

Table 2F-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° in accordance with the requirements in section 10.1.2.

Table 2F-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	
	θ_{null} (degrees)	R_{SLO} (degrees)*	θ_{null} (degrees)	R_{SLO} (degrees)*
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
Average of all recorded R_{SLO} values:				_____

* Include magnitude and algebraic sign in accordance with section 10.5.7.

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

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

Table 2F-8. Wind Tunnel Calibration of Three-Dimensional Probe

Wind Tunnel Facility: _____
 Wind Tunnel Location: _____
 Probe Type: _____
 Probe ID: _____
 Probe Calibration Date: _____
 Test Location: _____
 Calibration Pitot Tube Coeff. (C_p): _____
 Ambient Temperature ($^\circ F$): _____
 Barometric Pressure (P_{bar}): _____

Velocity Setting (ft/sec)	Pitch Angle	Calibration Pitot Tube		Tested Probe			Calc. F_1	Calc. F_2
		ΔP_{stat} (in. H ₂ O)*	Temp. ($^\circ F$)	$P_1 - P_2$ (in. H ₂ O)	$P_1 - P_3$ (in. H ₂ O)	Yaw Angle (degrees)		
	-30 $^\circ$							
	-25 $^\circ$							
	-20 $^\circ$							
	-15 $^\circ$							
	-10 $^\circ$							
	-5 $^\circ$							
	0 $^\circ$							
	5 $^\circ$							
	10 $^\circ$							
	15 $^\circ$							
	20 $^\circ$							
	25 $^\circ$							
	30 $^\circ$							

* Calibration pitot tube measurements must, at a minimum, be taken before the tested probe reading at the first pitch angle setting, and after the tested probe reading at the last pitch angle setting in each replicate. See section 10.6.11.

Table 2F-9. Calibration Log for Three-Dimensional Probe

Probe ID: _____

Probe Type: _____

Probe Calibration Date: _____

Test Location: _____

Nominal Velocity: _____

Pitch Angle	Average of All Repetitions		Number of Repetitions
	F_1	F_2	
-35°			
-30°			
-25°			
-20°			
-15°			
-10°			
-5°			
0°			
5°			
10°			
15°			
20°			
25°			
30°			
35°			