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GUIDELINES FOR DEVELOPMENT OF A QUALITY ASSURANCE PROGRAM: VOLUME I - DETERMINATION OF STACK GAS VELOCITY AND VOLUMETRIC FLOW RATE (TYPE-S PITOT TUBE)

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GUIDELINES FOR DEVELOPMENT OF A QUALITY ASSURANCE PROGRAM: VOLUME I - DETERMINATION OF STACK GAS VELOCITY AND VOLUMETRIC FLOW RATE (TYPE - S PITOT TUBE)

by

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ABSTRACT

Guidelines for the quality assurance of average stack gas velocity and volumetric flow rate measurements by the Federal reference method are presented. These include:

1. Good operating practices
2. Directions on how to assess performance and qualify data
3. Directions on how to identify trouble and improve data quality
4. Directions to permit design of auditing activities

The document is not a research report. It is designed for use by operating personnel.

This work was submitted in partial fulfillment of Contract Durham 68-02-1234 by Research Triangle Institute under the sponsorship of the Environmental Protection Agency. Work was completed as of June 1974.

SECTION I INTRODUCTION

This document presents guidelines for developing a quality assurance program for the determination of stack gas velocity and volumetric flow rate using Method 2. This method was published by the Environmental Protection Agency in the Federal Register, December 23, 1971, and is reproduced as Appendix A of this report for convenience of reference.

The objectives of this quality assurance program for Method 2 are to:

(1) minimize systematic and random variability in the measurement process,

(2) provide routine indications for operating purposes of unsatisfactory performance of personnel and/or equipment,

(3) provide for prompt detection and correction of conditions which contribute to the collection of poor quality data, and

(4) collect and supply information necessary to describe the quality of the data.

To accomplish the above objectives, a quality assurance program must contain the following components:

(1) recommended operating procedures,

(2) routine training and evaluation of personnel and evaluation of equipment,

(3) routine monitoring of the variables and parameters which may have a significant effect on data quality,

(4) development of statements and evidence to qualify data and detect defects, and

(5) action strategies to increase the level of precision/accuracy in the reported data.

Component (2) above is treated in the final report of the contract and component (5) is treated in the Quality Assurance Documents for pollutant specific methods which utilize the results of Method 2.

Implementation of a properly designed quality assurance program should enable measurement teams to achieve and maintain an acceptable level of precision in their velocity and flow-rate measurements. It will also allow a team to report an estimate of the precision of its measurements for each source emissions test.

Variability in emission data derived from multiple tests conducted at different times includes components of variation from:

(1) process conditions,

(2) equipment and personnel in field procedures, and

(3) equipment and personnel in the laboratory.

In many instances time and/or spatial variations in source output may be the most significant factors in the total variability. This component of variation is minimized by following the directions given in Method 1 for determining the number and location of traverse points and by being aware of the monitoring process fluctuations during sample collection. Quality assurance guidelines for Method 2 as presented here are designed to detect, control, and quantify equipment and personnel variations in both the field and the laboratory. In summary, the method is considered as an instantaneous velocity measurement at a point in time and space and not as an integral measurement over space and time. Also, it is assumed that the stack gas flow is parallel to the stack wall.

This document is divided into four sections or chapters. They are:

<u>Section I, Introduction</u> - The Introduction lists the overall objectives of a quality assurance program and delineates the program components necessary to accomplish the given objectives.

<u>Section II, Operations Manual</u> - The Operations Manual sets forth recommended operating procedures to assure the collection of data of high quality and instructions for performing quality control checks designed to give an indication or warning that invalid data or data of poor quality are being collected, thus allowing for corrective action to be taken before future measurements are made.

<u>Section III, Manual for Field Team Supervisor</u> - The Manual for a Field Team Supervisor contains directions for assessing data quality on an intra-team basis and for collecting the information necessary to detect and/or identify trouble.

<u>Section IV, Manual for Manager of Groups of Field Teams</u> - The Manual for Manager of Groups of Field Teams presents information relative to the test method (a functional analysis) to identify the important operations variables and factors, and statistical properties of and procedures for carrying out auditing procedures for an independent assessment of data quality.

The scope of this document has been purposely limited to that of a field and laboratory document. Additional background information is contained in the final report under this contract.

SECTION II OPERATIONS MANUAL

2.0 GENERAL

This Operations Manual sets forth recommended procedures for the measurement of stack gas velocity and the subsequent determination of volumetric flow rate according to Method 2. (Method 2 is reproduced from the Federal Register and is included as Appendix A of this document.) Quality control procedures and checks designed to give an indication or warning that invalid or poor quality data are being collected are written as part of the operating procedures and are to be performed by the operator on a routine basis. Results from certain strategic quality control checks will be used by the supervisor for the assessment of data quality.

The sequence of operations to be performed for each field test is given in Figure 1. Each operation or step in the method is identified by a block. Quality checkpoints in the measurement process, for which appropriate quality control limits are assigned, are represented by blocks enclosed by heavy lines. Other checkpoints involve go/no-go checks and/or subjective judgments by the test team members with proper guidelines for decision making spelled out in the procedures. Also, operations 6, 10, and 11 represented by blocks enclosed by dashed lines are to be carried out according to procedures given in Quality Assurance Documents for other methods. Specifically, Method 1 applies to operation 6, Method 4 to operation 10, and determination of molecular weight on a wet basis (operation 11) is accomplished by Method 3 combined with the results from Method 4. Quality assurance documents applicable to Methods 3 and 4 should be followed when performing Operations 10 and 11. In instances in which an item of equipment has sustained damage in the field, it may be necessary to check or recalibrate the item upon return to the laboratory. This possibility is indicated by the solid line originating prior to Operation 14 and terminating between Operations 1 and 2. The dashed line originating prior to Operation 3 and terminating at Operation 14 implies that in some cases the new calibration data may be used in the field data calculations.

The precision and/or validity of data obtained from this method depends upon equipment performance and the proficiency with which the operator performs his various tasks. From equipment calibration through on-site measurements, calculations, and data reporting, this method is susceptible to a variety of errors. Detailed instructions are given for minimizing or controlling equipment error, and procedures are recommended to minimize personnel error. Before using this document, the operator should study Method 2 as written in Appendix A in detail.

It is assumed that all apparatus satisfies the reference method specifications and that the manufacturer's recommendations will be followed when using a particular item of equipment. Also, when the Type-S pitot tube is strapped to a sampling probe as in Method 5, a minimum spacing between tube and probe of at least 1/2-inch or as recommended for the applicable method must be maintained.

PRE-SAMPLING PREPARATION

1. SELECT THE EQUIPMENT APPROPRIATE FOR THE PROCESS (SOURCE) TO BE TESTED. CHECK THE EQUIPMENT FOR PROPER OPERATION.

2. CALIBRATE EQUIPMENT WHEN 1) FIRST PURCHASED, 2) DAMAGED OR ERRATIC BEHAVIOR IS OBSERVED, OR 3) AFTER EVERY THIRD FIELD TEST OR THREE MONTHS, WHICHEVER OCCURS FIRST.

3. PACK EQUIPMENT IN A MANNER TO PRECLUDE BREAKAGE OR DAMAGE DURING HANDLING AND SHIPMENT.

ON-SITE VELOCITY MEASUREMENT

4. TRANSPORT EQUIPMENT FROM FLOOR LEVEL TO THE SAMPLING SITE BY THE BEST MEANS AVAILABLE.

5. ASSEMBLE THE EQUIPMENT ON-SITE AND PERFORM AN OPERATIONAL CHECK.

6. DETERMINE THE NUMBER AND LOCATION OF TRAVERSE POINTS ACCORDING TO METHOD 1.

7. DETERMINE THE INSIDE AREA OF THE STACK BY 1) MEASURING THE INSIDE DIMENSIONS USING A ROD AND THE SAMPLING PORTS, OR 2) MEASURING THE OUTSIDE CIRCUMFERENCE AND CORRECTING FOR WALL THICKNESS.

8. MARK THE PITOT TUBE TO ASSURE THAT MEASUREMENTS ARE MADE AT THE CORRECT POINTS WITHIN THE STACK.

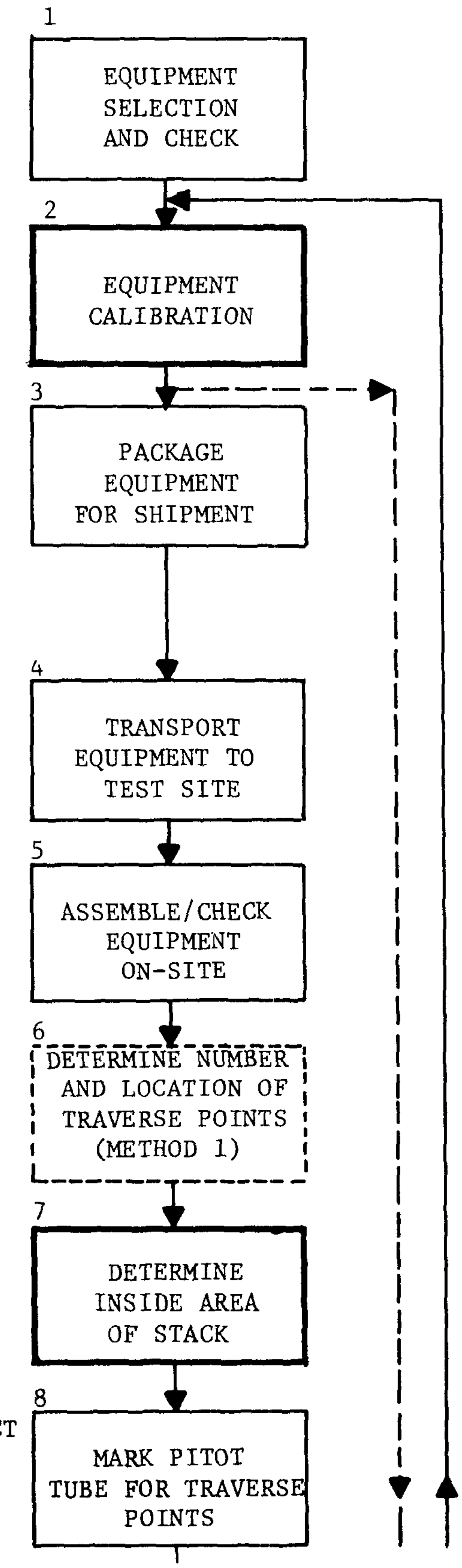


Figure 1: Operational Flow Chart of the Measuring Process

9. PERFORM THE VELOCITY TRAVERSE AS DIRECTED IN SUBSECTION 2.2.4 OF THIS DOCUMENT.

10. DETERMINE THE MOISTURE CONTENT OF THE STACK GAS USING THE QUALITY ASSURANCE DOCUMENT APPLICABLE TO METHOD 4.

11. DETERMINE THE MOLECULAR WEIGHT OF THE STACK GAS (WET BASIS) USING THE QUALITY ASSURANCE DOCUMENT APPLICABLE TO METHOD 3 AND THE RESULTS OF (10) ABOVE.

12. DISASSEMBLE AND INSPECT THE EQUIPMENT FOR SIGNS OF DAMAGE AFTER ALL MEASUREMENTS HAVE BEEN MADE AND RECORDED.

13. PACK THE EQUIPMENT FOR SHIPMENT BACK TO THE LABORATORY.

POST-SAMPLING OPERATIONS

14. PERFORM CALCULATIONS UTILIZING ANY NEW CALIBRATION DATA IF APPLICABLE.

15. FORWARD DATA WITH PERTINENT REMARKS CONCERNING QUALITY CHECKS FOR FURTHER INTERNAL REVIEW OR TO USER.

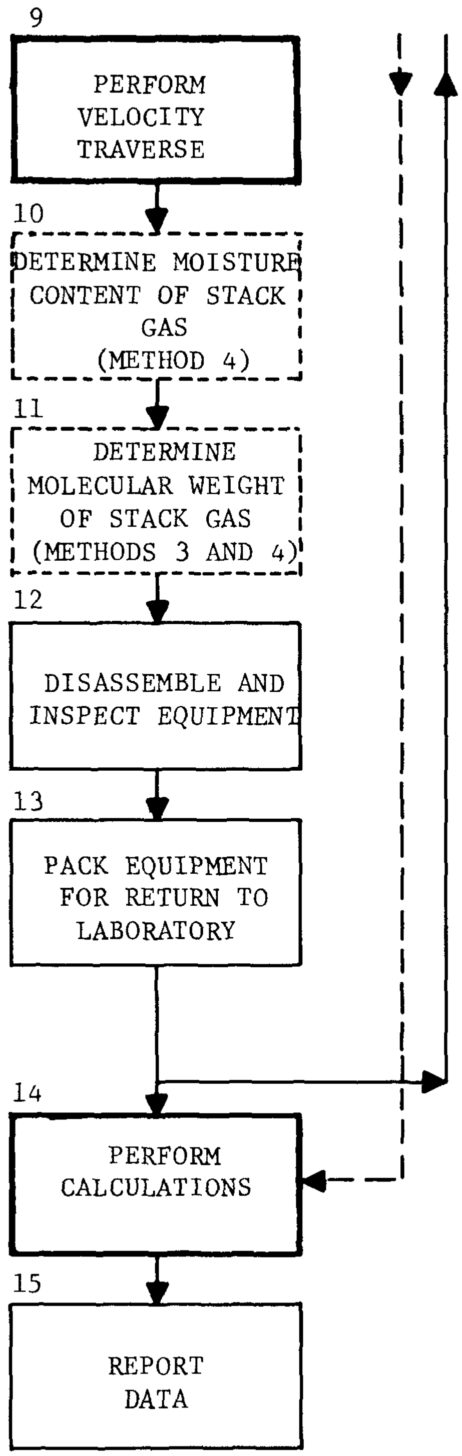


Figure 1: Operational Flow Chart of the Measuring Process (Continued)

For discussion purposes the measurement process is divided into three phases. They are:

(1) pre-sampling preparation,

(2) on-site measurements, and

(3) post-sampling operations.

The pre-sampling preparation phase consists of equipment inspection, calibration, and the packing of equipment for transporting to the test site area. Unpacking and assembly of equipment, gas velocity measurements, data recording, and packing the equipment for shipment back to the home laboratory are included in the on-site measurement phase. Post-sampling operations include calculations and data reporting. Each phase is discussed separately.

2.1 PRE-SAMPLING PREPARATION

Knowledge of certain characteristics of the process output to be tested is needed for correct selection of apparatus to be used in the field. For example, if the stack gas temperature, pressure, and velocity ranges are known, a differential pressure gauge with the smallest division marks over the expected velocity range should be selected. This would tend to minimize the reading error associated with the ΔP measurements. Also, the stack gas temperature could dictate whether an unshielded or shielded thermocouple should be used, for example.

2.1.1 Apparatus Selection and Check

2.1.1.1 Calibration Pitot Tube and Differential Pressure Gauge - The Type-S pitot tube to be used in field tests should be calibrated against a standard pitot tube or a Type-S pitot tube that has been calibrated by the National Bureau of Standards and is maintained and used only in the laboratory environment. Also, a differential pressure gauge, such as an inclined manometer, and sufficient connecting lines are required. It is recommended that the same differential pressure gauge be used for both the calibration pitot tube and the pitot tube being calibrated.

2.1.1.2 Type-S Pitot Tube and Differential Pressure Gauge - A Type-S pitot tube and an inclined manometer assembly is illustrated in Figure 2-1 of Appendix A. The following checks should be made before each field test.

Visually inspect the pitot tube openings for damage such as a scratch, nick, or dent that would tend to disrupt the air flow pattern. Check for proper alignment; i.e., the centers of the two openings should be in a straight line such that when one opening is directed correctly upstream, the other will be exactly 180° opposite, pointing downstream (Ref. 1). If the damage or misalignment is obvious when viewed with the naked eye, the pitot tube should be replaced or repaired. Check the weld spots holding the two legs together; if broken, repair.

Check the quick disconnects on the pitot tube and the tube lines for proper operation. Clean the small metal parts of the disconnect. A drop of penetrating oil will help to keep them free.

Blow out the pitot tube legs from the line ends with compressed air, rinse with distilled water then with acetone, and dry with compressed air.

Check the pitot tube lines for leaks by connecting one end of a line to a 36-inch U-tube mercury manometer. Connect the other end to a vacuum pump and pull a vacuum of at least 10 inches of mercury. Seal the tubing on the pump side and check for leaks by observing the mercury manometer. Repeat the procedure for the other line. If leakage is observed, lightly pressurize the line and check for leaks with soapy water or by submerging the line in a water bath. Repair or replace as necessary.

Visually inspect the differential pressure gauge for damage. Repair or replace as necessary. Level the inclined manometer (if used as the differential pressure gauge) and fill with the recommended fluid. The recommended fluid is usually inscribed on the manometer. Check for leaks, especially around the fluid level plunger and drain screws. Replace the fluid level plunger or O-rings if leaks are detected. The manometer should be cleaned when dirty and the fluid changed at any sign of fading. If other differential pressure gauges are used, follow the manufacturer's check-out instructions.

Connect the pitot tube and differential pressure gauge with the pitot tube lines. Check for obstructions by blowing lightly on one pitot tube leg, then the other, and watching the response of the guage.

2.1.1.3 Temperature Measurement System - The temperature measuring system must satisfy the criteria given in 2.3 of Appendix A. Systems comprised of a remote reading thermometer (mercury in stainless steel), a thermocouple with a readout device, and a thermister with a readout device have been used and found satisfactory when properly maintained. The following checks should be made before each field test.

(1) Visually check the readout device, sensor, and interconnecting lines or wires as applicable for general appearance. If damage is detected, repair or replace as necessary.

(2) Compare absolute ambient temperature readings as made with the temperature measuring system to those made with a mercury-in glass thermometer. If the system does not agree within ± 7°F (this is less than ± 1.5 percent at about 530°R which is near room temperature) of the thermometer, the temperature-measuring system should be calibrated as directed in subsection 2.1.2.2, page 14. Otherwise, record the two readings

in the calibration log book, date and initial the entry. Accept the system as satisfactory.

2.1.1.4 Barometer - Check the field barometer reading against that of a mercury barometer. If they disagree more than ± 0.1 inches of mercury (approximately ± 0.3 percent at 29.92 inches of mercury), adjust the field barometer until it agrees with the mercury barometer. Record the two readings in the calibration log book, date and initial the entry. Accept the barometer as satisfactory.

2.1.2 Calibration of Apparatus

2.1.2.1 Type-S Pitot Against a Standard Pitot Tube - The Type-S pitot tube should be calibrated against a standard pitot tube (or an NBS-calibrated Type-S pitot tube) when first purchased, after a field test in which visible physical damage is sustained, or after every third field test or every three months, whichever occurs first.

A test setup for calibrating the pitot tube can be constructed in the laboratory from a straight section of the tube or duct 12 inches or larger in diameter (the projected area of the inserted pitot tube should not be greater than about 1 percent of the duct cross-sectional area) and approximaterly 12 diameters long. A blower capable of generating air velocities covering the range to be measured in the field tests is required. A large-capacity, all-purpose blower can be utilized in conjunction with a variable choke on the intake side of the blower to obtain different velocities. Holes (ports) are placed a minimum of 8 diameters downstream from the blower (exhaust exit) and 2 diameters upstream from the tube or duct exit. See Reference 2 for a more detailed discussion on the design of a calibration test setup.

For velocity pressures within the limits of about 0.01 to 10 inches of water at laboratory conditions, a well-made standard pitot tube has a coefficient $C_{P_{std}}$, which ranges from about 0.98 to 1.00. The actual lower limit for velocity pressure for which the coefficient remains below 1.00 depends on the outside diameter (OD) of the tube. For example, a standard pitot tube with a 1/4-inch OD may not have a coefficient within the above range for pressures below about 0.05 inches of water (Ref. 1). In general, a pitot tube with a larger OD will retain a coefficient of less than 1.0 at lower velocity pressures.

If the coefficient has not been specified by the manufacturer and the pitot tube has not been calibrated by the NBS, it is customary to assume a value of 0.99 within the above velocity pressure range.

The Type-S pitot tube coefficient varies not only from one tube to another but also as a function of air velocity for the same pitot tube. For this reason it is important to calibrate the Type-S tube over the velocity range that is expected in the field operation. The calibration coefficient of a Type-S pitot tube should seldom fall outside the range of 0.85 ± 0.02.

If a calibration shows the coefficient to be outside this range, it is suggested that the standard pitot tube, calibration setup, and calibration technique be checked and the calibration rerun before accepting it as valid. If the second coefficient is outisde the range of 0.85 $\pm$ 0.02, the two values should agree within $\pm$ 0.01, and the two values should be averaged. Poor calibration technique is indicated if they do not agree within $\pm$ 0.01.

Note: If the coefficient is outside the range of 0.85 $\pm$ 0.02 and the pitot tube is subsequently used in isokinetic sampling, adjustment should be made on the nomograph used for isokinetic operations. Directions for making the adjustment are given in the quality assurance documents applicable to methods requiring isokinetic sampling.

When a Type-S pitot tube is first purchased, a calibration curve covering the range from about 0.01 to 10 inches of H_2O should be developed as follows:

(1) Assemble the apparatus as shown in Figure 2-1 of Appendix A.

(2) Level and zero the inclined manometer (or differential pressure gauge).

(3) Adjust the calibration setup to give a desired air velocity (or velocity head) as measured by the standard pitot tube.

(4) Mark both pitot tubes so that they will be measuring at the same point in the duct. The measuring point must be such that the tip of neither pitot tube is closer than 1 inch to the duct wall.

(5) Insert the standard tube to the correct point and align the tube with the air flow. Seal the port with a sponge or rag as well as possible to minimize the disturbance in the air flow.

(6) Read and record the velocity head, ΔP_{std}, in Table 1.

(7) Remove the standard tube from the port and insert the Type-S tube, being careful to locate the tube tip at the same point in the duct as that measured by the standard tube. This will require two ports positioned so that the same point will be measured by both pitot tubes.

Note: It is recommended that, if possible, the same differential pressure gauge be used for both tubes. Quick disconnects on the pitot-tube lines make this operation easy and quick.

(8) Align the Type-S tube with leg A (the legs should be marked for easy identification at all times) facing upstream. Alignment of the pitot tube along the roll and pitch axes is best accomplished by visually aligning it against the stack. Figures 2 and 3 illustrate the magnitude and characteristics of measurement errors in ΔP associated with varying degrees of nonalignment on the roll and pitch axes, respectively (Ref. 3).

(9) Read and record the velocity head, ΔP_{test}, in Table 1.

(10) Repeat the above steps for velocities covering the range expected in the field.

(11) Repeat the complete procedure with leg B of the Type-S pitot tube facing upstream.

(12) Calculate the Type-S pitot tube coefficient, Cp_{test}, for each set of measurements using equation 2-1 of Appendix A.

(13) Construct a calibration curve as shown in Figure 4 for both leg A and leg B of the Type-S pitot tube. (In plotting a calibration curve over the entire range of 0.01 to 10 inches of H_2O, the ΔP scale in Figure 4 should be expanded so as not to compress the 0.0 to 0.1 interval.) Construct a smooth, eye-fit curve to the data. In general, the calibration curve should be linear throughout the ΔP range. If the curve starts up in a nonlinear manner at the low end of the ΔP scale, it is possible that the coefficient of the standard pitot tube is varying. If the Type-S tube is to be used in this low range, it would be desirable to have the standard pitot tube calibrated by the NBS or to try a standard pitot tube with a larger outside diameter, if possible, to extend the calibration curve on the lower end.

(14) Check all plotted points and rerun any than deviate more than $\pm$ 0.01 from the eye-fit curve on the C_p axis.

(15) Compare the calibration curves for the two legs of the Type-S pitot tube. If at any point on the ΔP axis the two curves differ by more than 0.01, the reference method specifies that the pitot tube not be used (see subsection 4.3 of Appendix A).

Table 1. SAMPLE TABLE FOR RECORDING PITOT TUBE CALIBRATION DATA

Calibration Pitot Tube: Type_________Size (OD)_________ID Number______

Type-S Pitot Tube ID Number____

Calibration: Date_______________Performed by_________________________

Legs* A,B	Velocity Head (inches of H_2O)	ΔP_{test} (inches of H_2O)	ΔP_{std} (inches of H_2O)	$C_{P_{test}}$ (dimensionless)
A B	0.01			
A B	0.02			
A B	0.04			
A B	0.06			
A B	0.08			
A B	0.10			
A B	0.2			
A B	0.4			
A B	0.6			
A B	0.8			
A B	1.0			
A B	1.2			
A B	1.5			
A B	1.75			
A B	2.0			
A B	3.0			
⋮	⋮			
A B	10.0			

*Identify the legs of the Type-S pitot tube as leg A and leg B.

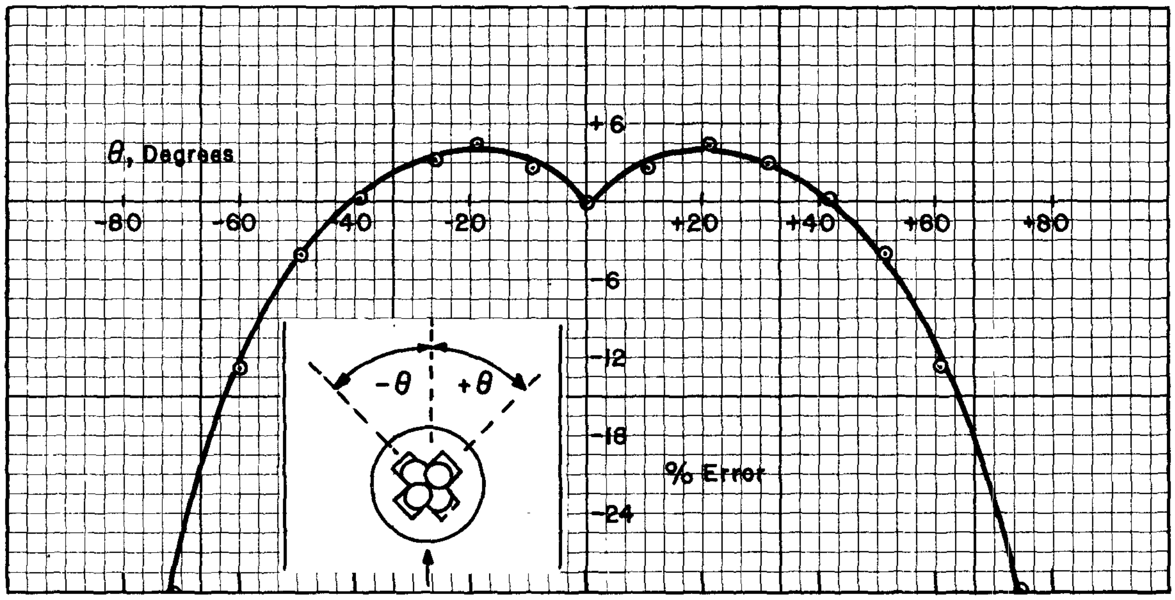


Figure 2: Example of Error in Measured Stack Gas Velocity as a Function of Tube Misalignment Along Its Roll Axis

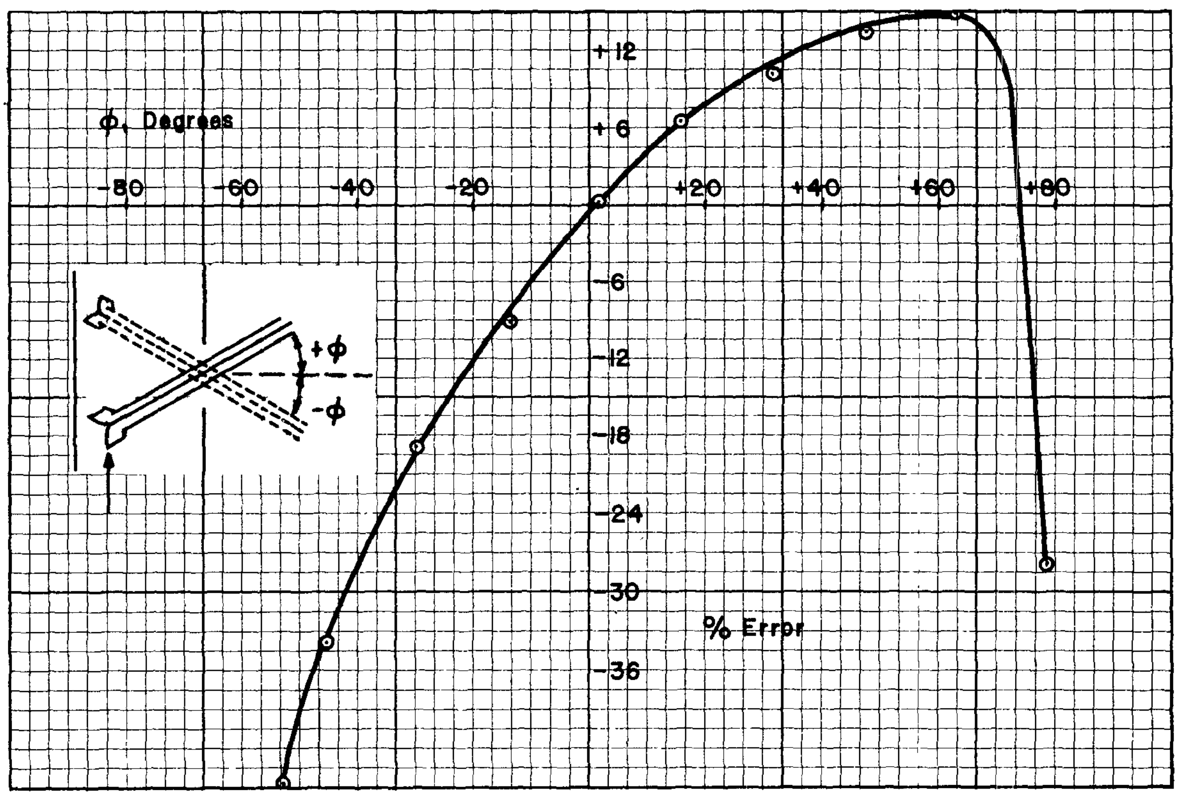


Figure 3: Example of Error in Measured Stack Gas Velocity as a Function of Tube Misalignment Along Its Pitch Axis

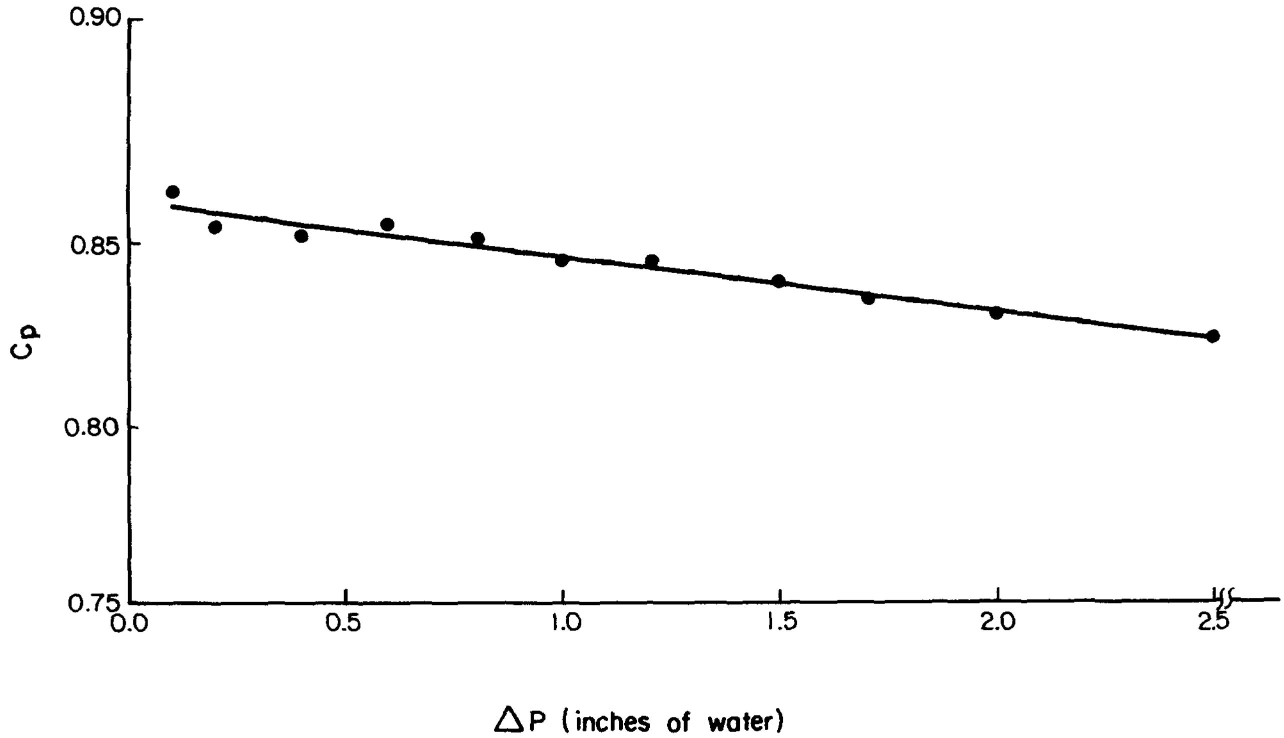


Figure 4. Hypothetical Type-S Pitot Tube Calibration Curve.

(16) From the calibration curve estimate an average coefficient value, $C_{P_{avg}}$, for the velocity pressure range expected in the field. Obtain from the graph the maximum coefficient, $C_{P_{max}}$, and the minimum coefficient, $C_{P_{min}}$, within the above velocity pressure range. Compute

(1) $$\frac{C_{P_{max}} - C_{P_{avg}}}{C_{P_{avg}}} \times 100$$

and

(2) $$\frac{C_{P_{avg}} - C_{P_{min}}}{C_{P_{avg}}} \times 100$$

If either (1) or (2) above is greater than 5 percent, the pitot tube does not satisfy the reference method (see subsection 2.1 of Appendix A) specifications.

Once the calibration curve has been developed as directed above, future calibrations can be made at two or three points in the velocity range of interest and compared to the original calibration curve. The original calibration curve should be used as long as the test points fall within $\pm$ 0.01 (this is about $\pm$ 1.2 percent of C_P) of the eye-fit curve. A new curve should be developed when one or more test points (from the same test) fall outside the above limits. (The coefficient of a pitot tube seldom changes unless the tube has been severely damaged; therefore, it is always advisable to check the equipment and technique and then rerun any data points that are in question before changing the original calibration curve.)

The reference method (see subsection 4.1 of Appendix A) recommends that the Type-S pitot tube calibration be repeated after use at each field site. The minimum frequency of scheduled calibrations suggested here is once every three field tests or after three months, whichever occurs first. Unscheduled calibrations should be performed at any sign of damage to the pitot tube.

2.1.2.2 <u>Stack Gas Temperature Measuring System</u> - A system capable of measuring the stack gas temperature to within 1.5 percent of the minimum absolute stack temperature is required. A high-quality mercury bulb thermometer readable to the nearest °F and calibrated in an ice bath and in boiling water (with pressure corrections) is an acceptable laboratory standard for calibration of temperature-measuring systems.

The temperature-measuring system should be checked as directed in Subsection 2.1.1.3 before each field test. The minimum frequency of scheduled system calibration, as described above, is once every three field tests or after three months, whichever occurs first.

The calibration procedure is as follows:

(1) Calibrate the temperature-measuring system against a mercury bulb thermometer in 1) an ice water bath, 2) boiling water, and 3) a tube furnace or a mineral oil bath if higher temperature calibration points are desired.

(2) Adjust the readout device (follow manufacturer's instructions) to agree with the mercury thermometer or construct a calibration curve of system output versus temperature as read by the mercury thermometer.

(3) Record the measurements to the nearest °F in a calibration log book. Date and sign the entry.

2.1.2.3 <u>Barometer</u> - The barometer calibration should be checked and necessary adjustments made as directed in Subsection 2.1.1.4 before each field test.

Record the measurements in a calibration log book. Date and sign the entry.

2.1.3 Packing Equipment for Shipment

This aspect of *any* source testing method in terms of logistics, time of sampling, and quality of data is very dependent upon the packing of equipment in regards to 1) accessibility in the field, 2) ease of movement on site, and 3) optimum functioning of measurement devices in the field. Equipment should be packed under the assumption that it will receive severe treatment during shipping and field operation.

2.1.3.1 Type-S Pitot Tube - Pack the pitot tube in a case protected by styrofoam or other suitable packing material. The case should have handles which can withstand hoisting and be rigid enough to prevent bending or twisting of the pitot tube during shipping and handling.

2.1.3.2 Differential Pressure Gauge - Close all valves on the pressure gauge. Pack it in a suitable case for shipment. Spare parts, such as O-rings and operating fluid (inclined manometer), should also be packed.

2.1.3.3 Temperature-Measuring System - Proper packaging of the temperature measuring systems depends on the type of system used. In general the sensor and leads can be protected from breakage or other damage during shipment by securing them to the pitot tube and enclosing them with suitable packing material. The readout device, if detachable from the sensor, should be packed in a separate case.

2.1.3.4 Barometer - The barometer should be packed in a shock-mounted (spring system) carrying case.

2.2 VELOCITY MEASUREMENT ON-SITE

The on-site measurement activities include transporting the equipment to the test site, unpacking and assembling the equipment, making the velocity measurements, and inspecting and repacking the equipment for shipment back to the home laboratory.

2.2.1 Transport of Equipment to the Sampling Site

The most efficient means of transporting or moving the equipment from floor level to the sampling site as decided during the preliminary site visit should be used to place the equipment on-site. Care should be exercised against damage to the test equipment during the moving phase.

2.2.2 Assembly of the Test Equipment

Assemble the test equipment and check for proper operation in the same manner as was used during PRE-SAMPLING PREPARATION.

2.2.2.1 Type-S Pitot Tube and Differential Pressure Gauge - Connect the pitot lines between the Type-S pitot tube and the inclined manometer as shown in Figure 2-1 of Appendix A. Recheck for crimped or blocked connecting lines.

Check the direction of the Type-S pitot tube leg (impact side) to be sure it is connected to the inclined manometer in the correct position; otherwise, manometer fluid (gauge oil) will be forced into the manometer lines. If manometer fluid is inadvertently forced into the lines, the fluid must be removed, the lines cleaned and reassembled.

The inclined manometer must be mounted or located so it is free from the effects of vibrations and convenient for reading. The manometer must be properly leveled, and the oil column accurately zeroed and freed of bubbles before use.

All connections should be checked for tightness to guard against system leaks.

2.2.2.2 Temperature Measuring System - Visually check the temperature-measuring system, including sensor and readout, for physical damage. Check for proper operation by comparing the ambient temperature as indicated by the system with that indicated by a mercury bulb thermometer. If the system's reading varies more than 7°F from that indicated by the thermometer, the cause of the difference should be determined and corrected by repair or replacement of system components before beginning the velocity traverse.

2.2.2.3 Barometer - Set up the barometer and check for proper operation by calling the nearest airport or weather bureau to get its station pressure and comparing it to the barometer reading. Accept the barometer reading if they are within ± 0.6 inches of mercury. Pressure as reported by airports and weather bureaus is usually corrected to sea level; the uncorrected or station pressure must be requested for this use.

2.2.3 Measurement of the Inside Dimensions of the Stack

An accurate determination of the stack's cross-sectional area is important when computing volumetric flow rate (see subsection 3.3.1.3). Also, the inside dimensions must be known to properly mark the pitot tube for making a velocity traverse. However, field team members should always use their good judgment and experience in selecting the best method of measuring stack dimensions for each particular situation. Two commonly used methods of measuring stack dimensions are discussed.

(1) In most instances the use of a rigid rod, made of metal or other material that will withstand stack conditions, inserted through a sampling port is the easiest and most accurate method of measuring the dimensions of small stacks (i.e., diameter or length and width). Measurements should be made to the nearest 1/8 inch and converted to the nearest 0.01 foot.

Caution: When testing a stack that has hot and/or noxious gases at a positive pressure, a packing gland should be used to prevent the gases from escaping from the sampling port. Also, asbestos gloves should be worn when working around a hot stack.

Because all circular stacks are not perfect circles and all sides of a rectangular stack are not straight, best results are obtained if the dimension is measured from as many sampling ports as available at the sampling site. The average value is calculated and used for subsequent calculation of the volumetric flow rate.

The cross-sectional area of the stack should be sketched on the form in Figure 5 with all measured dimensions and their values shown. The average value is recorded on the same form in the blank left for stack diameter in feet. (If the stack is rectangular, the average length and width should be recorded in this space with diameter marked out.)

(2) For stacks too large or inconvenient for measuring with a rod as described in (1) above, the next best method may be to measure the outside circumference and calculate the inside diameter by

$$d = C/\pi - 2t$$

where d = inside diameter of the stack (ft),

C = outside circumference of stack (ft),

$\pi \simeq 22/7$, and

t = stack wall thickness (ft).

All lengths should be measured to the nearest 1/8 inch and converted to the nearest 1/100 (0.01) foot.

The cross-sectional area of the stack should be sketched on the form in Figure 5. Record the calculated inside diameter on the same form and indicate that it was derived from the circumference measurement.

2.2.4 Mark the Pitot Tube for Traverse Points

Using the stack dimensions from above, determine the location and number of traverse points as directed in Method 1 of the Federal Register, Vol. 36, No. 247, December 23, 1971. The pitot tube can be marked for the traverse points by utilizing a china marker or asbestos tape. In instances in which it is difficult or impossible to see the inside edge of the port, the probe should be marked so as to allow the use of the outside edge of the stack (or packing gland) as an index.

2.2.5 Make Velocity Measurements

The number and location of traverse points and sampling ports are determined by Method 1. It is suggested that for circular stacks less than 10 feet in diameter, two ports along diameters at right angles to each other and in the same plane are sufficient. However, when the stack diameter is greater than 10 feet, the use of four ports, one at each end of the two diameters, if available, would avoid the use of extensions on the pitot tube. If it is necessary to use a Type-S pitot tube longer than about 10 feet, it should be structurally reinforced to prevent drooping of the tube and result in the type of error illustrated in Figure 3, page 12.

TEST IDENTIFICATION

PLANT: NAME____________________ LOCATION: ____________________

STACK NO. _______________

DATE______________ TEAM: LEADER______________________________

OPERATORS______________________________

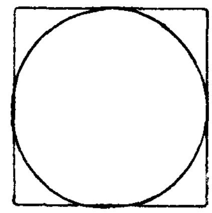
____

SAMPLING SITE DESCRIPTION

UPSTREAM DISTURBANCE_______diameters

DOWNSTREAM DISTURBANCE_____diameters

STACK DIAMETER_______ft



STACK CROSS SECTION

APPARATUS IDENTIFICATION

PITOT TUBE NO.______ UPSTREAM LEG______________ COEFFICIENT, C_p______

DIFFERENTIAL PRESSURE GAUGE: RANGE (inches of H_2O)____________

DIVISION (inches of H_2O)__________

MEASURED RESULTS

$(V_s)_{avg}$ _______ft/sec Q_s_______ ft^3/hr

CALCULATED RESULTS

V_s_________ ft/sec

RECORDED TEST DATA

Sample Point	Traverse Point Number	Clock Time	Velocity Head, ΔP (inches of H_2O)	$\sqrt{\Delta P}$	Stack Temp. T_s(°R)*	$\sqrt{T_s}$	Remarks
	⋮		⋮		⋮		
			AVERAGE:		AVERAGE:		

$*T_s(°R) = °F + 460$

Figure 5. Sample Data Form for Velocity Traverse.

The plant engineer or other designated plant liaison should be contacted prior to the traverse to make sure that the process is operating and stabilized at the required capacity and that it continues to do so throughout the traverse.

2.2.5.1 Special Precautions - Before and during the traverse a number of precautions should be taken. They are:

(1) For safety reasons and for efficiency in the measurement process, the pitot tube should be short enough to allow for easy handling from outside the stack when held at any traverse point.

(2) The impact opening should always point directly upstream into the flowing gases. The alignment should be made visually with reference to the stack geometry and not by rolling or tipping the pitot tube until a maximum response is observed (see Figure 2 and 3).

(3) If the gas stream contains a significant concentration of particulates, both legs of the pitot tube should be blown out frequently during the velocity traverse.

(4) When making a velocity measurement, all unused sampling ports must be plugged and the port being used sealed as tightly as possible to minimize any effect on the static pressure or possibly change the angle of impact of the stack gas with the pitot tube opening. The port being used can be sealed with asbestos material, a pre-cut sponge, or just a piece of cloth, according to the temperature of the stack gas.

(5) When testing a stack that has hot and/or noxious gases under positive pressure, a packing gland should be used to prevent the gases from escaping from the sampling port. Also, asbestos gloves should be worn when working around a hot stack.

(6) Damage or suspected damage to any item of equipment, such as a pitot tube or inclined manometer, during the test should be fully documented at the time it occurs or at first awareness of its occurrence. The item should be replaced by a spare if available. If it is necessary to continue using the damaged item, a post-test calibration should be performed and the new calibration used for the data collected after the damage occurred.

2.2.5.2 Traverse Procedure - The recommended procedure is to measure the velocity head and temperature twice at each traverse point accessible from a given port by measuring each point once as the pitot tube is inserted into the stack and moved across the stack's diameter and repeating the measurements as the pitot tube is withdrawn from the port. Care should be exercised not to touch the probe tip to the side of the stack to prevent damage to or clogging of the tip.

Each sampling port and traverse point should be identified by a number or letter. A sketch of the stack with all dimensions, traverse points, and sampling ports properly identified should be made on the form in Figure 5. Record the clock time, ΔP, and T_s for each traverse point on the form in Figure 5.

Check with the plant engineer or designated plant liaison to verify that the process was operating at the desired capacity during the traverse. If the process was operating at the desired capacity, accept the traverse as valid; otherwise, do another traverse after the engineer has the process operating and stabilized at the desired capacity.

2.2.5.3 Measurement of the Static Pressure of the Stack - Three acceptable means of measuring static pressure are given in the order of decreasing acceptability. The methods are:

(1) Drill a tap perpendicular to the stack gas flow (or use a sampling port if a good seal can be maintained) and connect one side of a U-tube mercury manometer to the tap. Vent the other side of the manometer to the atmosphere.

(2) A second method is to use the static pressure tap of a standard pitot tube connected to one side of an inclined manometer. (If the stack pressure is obviously positive, the static pressure tap would be connected to the pressure side of the manometer; if it is obviously negative, connect the static pressure tap to the other side of the manometer; otherwise trial and error will have to suffice.) The remaining side of the manometer is vented to the atmosphere. Point the pitot tube pressure opening directly upstream and seal the port around the tube.

(3) A less accurate method is to use a Type-S pitot tube with the opening face parallel to the gas stream. Only one leg of the pitot tube should be connected to the manometer. The other side of the manometer is vented to the atmosphere. Extreme care should be taken to align the probe properly and to seal the port around the pitot tube.

Note: If Method 2 or 3 is used and the pressure is read in inches of water, convert to inches of mercury by multiplying by 0.0735 (slide rule accuracy).

Record the static pressure, P_g, (be sure to include the sign) as read from the manometer on the form in Figure 5. Compute the absolute stack pressure, P_s, by

$$P_s = P_{bar} + P_g$$

where P_{bar} is the barometric pressure read from the barometer.

2.2.5.4 Data Validation - As a check on the validity of the measured average stack gas velocity, it is suggested that process data be obtained and used to calculate an average velocity. Both the calculated and measured values should be recorded on the form in Figure 5. No definite, rigid guidelines can be given as to how well these two values should agree. However, if they disagree by as much as 50 percent, the traverse probably should be repeated. (Several such comparisons made on a power plant agreed within $\pm$ 20 percent (Ref. 4).) In general, the measured values will tend to be higher than the calculated values. A sample calculation of stack gas velocity using process data is given in Reference 4. Also, a set of nomographs and instructions for performing these calculations are available commercially (Ref. 5). These calculations should be performed before starting data collection and compared to the measured values as soon as they are obtained to allow for repeating the traverse if necessary.

2.2.6 Inspect and Pack Equipment for Return to Laboratory

Disassemble, clean, inspect, and repack the pitot tube, manometer, thermocouple readout, pitot lines, and barometer into their respective cases for shipment back to the laboratory.

As the equipment is disassembled and cleaned, a visual post-test check is made for signs of damage that were not detected during the test. If a piece of equipment was unknowningly damaged during the test, it should be checked and, if applicable, calibrated upon arrival at the laboratory.

The original calibration values are used for calculating the volumetric flow rate for the field test. However, the old and new calibration values should be forwarded to the supervisor along with the field test data.

All data sheets should be dated and signed by the field team director at the time of the test. Preserve data sheets for final calculations. It is advisable to have duplicate data sheets and hand carry or ship one set with the equipment and mail the other set to the laboratory.

2.3 POST-SAMPLING OPERATIONS

2.3.1 Calculations

Equation 2-2 in Appendix A is used to calculate the average stack gas velocity at stack conditions. Compute the averages of the $\sqrt{\Delta P}$ and $\sqrt{T_s}$ columns in Figure 5 for values of $(\sqrt{\Delta P})_{avg}$ and $(\sqrt{T_s})_{avg}$, respectively. Also, obtain the correct C_p from the pitot tube calibration curve (see Figure 4, page 13) by using the value of $(\sqrt{\Delta P})^2_{avg}$ just calculated. The molecular weight on a wet basis, M_s, is obtained from Method 3 utilizing the results of Method 4; and the absolute stack gas pressure, P_s, is obtained from the form in Figure 5. Record the calculated average stack gas velocity, $(V_s)_{avg}$, on the form in Figure 5.

It should be noted here that to be technically correct, the term $(\sqrt{T_s})_{avg}$ should be used. However, since T_s is large (i.e., usually 500°R or greater), the term $\sqrt{(T_s)_{avg}}$ as given in the reference method can be used with a less than 1-percent error if the range in T_s is not greater than 50°F.

Use equation 2-3 of Appendix A to calculate the stack gas volumetric flow rate in standard cubic feet per hour on a dry basis. The average velocity calculated above is used for V_s. The cross-sectional inside area of the stack, A, is calculated by:

(1) For circular stacks, $A = (1/4)\pi\ (\text{diameter})^2$.

(2) For rectangular stacks, $A = (\text{length}) \times (\text{width})$.

A value for B_{wo}, the proportion by volume of water vapor in the gas stream, is obtained from Method 4.

Record the calculated volumetric flow rate, Q_s, on the form in Figure 5.

In situations where it is not necessary to calculate a value for the average stack gas velocity, it would simplify the calculations to determine the volumetric flow rate at standard conditions directly by

$$Q_s = 5.45 \times 10^6 (1 - B_{wo})\ A\ C_p\ (\sqrt{\Delta P})_{avg} \left[\frac{P_s}{M_s\ (T_s)_{avg}}\right]^{1/2}$$

where all terms are in the units as given in equations 2-2 and 2-3 of Section 4 in Appendix A and the range of T_s is less than 50°F.

This latter method eliminates the compounding of errors due to terms common to both equations 2-2 and 2-3--namely, P_s and $(T_s)_{avg}$. This effect, however, should be small compared to the overall measurement variability.

Calculation error due to procedural or mathematical mistakes can be a large component of total system error. Therefore, it is recommended that each set of calculations be repeated, starting with the raw field data, preferably by a team member other than the one that performed the original calculations. If a difference greater than typical round-off error is observed, the calculations should be checked step by step until the source of error is found and corrected.

The check values should be recorded in parentheses beside the original calculated values on the form in Figure 5. The checker should initial the entry, and a copy of the completed form should be filed in the laboratory log book.

2.3.2 Data Reporting

A completed copy of the form in Figure 5 as approved and signed by the supervisor should be forwarded for additional internal review or to the user.

SECTION III MANUAL FOR FIELD TEAM SUPERVISOR

3.0 GENERAL

The term "supervisor" as used in this document applies to the individual in charge of a field team. He is directly responsible for the validity and the quality of the field data collected by his team. He may be a member of an organization which performs source sampling under contract to government or industry, a government agency performing source sampling, or an industry performing its own source sampling activities.

It is the responsibility of the supervisor to identify sources of uncertainty or error in the measurement process and, if possible, eliminate or minimize them by applying appropriate quality control procedures to assure that the data collected are of acceptable quality. Specific actions and operations required of the supervisor for a viable quality assurance program are summarized in the following listing.

(1) Monitor/Control Data Quality

(a) Direct the field team in performing field tests according to the procedures given in the Operations Manual.

(b) Perform or qualify results of the quality control checks (i.e., insure that checks are valid).

(c) Perform necessary calculations and compare quality control checks to suggested performance criteria.

(d) Make corrections or alter operations when suggested performance criteria are exceeded.

(e) Forward qualified data for additional internal review or to user.

(2) Routine Operation

(a) Obtain from team members immediate reports of suspicious data or malfunctions. Initiate corrective action or, if necessary, specify special checks to determine the trouble; then take corrective action.

(b) Examine the team's log books periodically for completeness and adherence to operating procedures.

(c) Approve data sheets, calibration data, etc., for filing.

(3) Evaluation of Operations

   (a) Evaluate available alternative(s) for accomplishing a given objective in light of experience and needs.

   (b) Evaluate operator training/instructional needs for specific operations.

Consistent with the realization of the objectives of a quality assurance program as given in Section I, this section provides the supervisor with brief guidelines and directions for:

(1) collection of information necessary for assessing data quality on an intra-team basis;

(2) isolation, evaluation, and monitoring of major components of system error;

(3) collection and analysis of information necessary for controlling data quality.

3.1 ASSESSMENT OF DATA QUALITY (INTRA-TEAM)

Intra-team or within-team assessment of data quality as discussed herein provides for an estimate of the precision of the measurements made by a particular field team. It does not provide the information necessary for estimating measurement bias (see Subsection 4.1.2 for a discussion of bias). However, if the operating procedures given in the Operations Manual (Section II) and directions for locating sampling ports and determining the number of traverse points as given in Method 1 are followed, the bias should be small in most cases. [illegible] performance of an independent quality audit which would make possible an inter-team assessment of data quality is suggested and discussed in Subsection 4.2 of the MANUAL FOR MANAGER OF GROUPS OF FIELD TEAMS.

Assessing data quality for a field team involves 1) adhering to good operating practices and 2) performing periodic quality control checks (i.e., calibration checks) to verify that the equipment is satisfying certain performance criteria. For field tests in which both of the above conditions have been met, a statement of the precision of the measurement can be made. The procedure for making an assessment of data quality is to make engineering judgments on the magnitude of operational errors and use the results of quality control checks to evaluate equipment performance. The procedure is explained in the following subsections in terms of the required information, how to collect the required information, treatment of the collected information, and reporting data quality.

3.1.1 Required Information

Information required for data assessment by this technique includes estimates of operational error and verification that the equipment is performing within specifications. Assumptions are made for the operational errors in Subsection 3.3.1, Identification of Important Variables. Equipment error is estimated, by observing through calibration or quality control checks, that suggested performance criteria are met. Suggested performance criteria are discussed in Subsection 3.2. Performance criteria are required for the Type-S pitot tube, temperature-measuring system, and the barometer. Once the performance criteria have been set and reasonable estimates of the operational error range have been made, the variability of the measured gas velocity or volumetric flow rate can be calculated using the method described in Subsection 4.1.1 of the Management Manual. Specifically, Table 4, page 46 illustrates how to calculate the coefficient of variation for volumetric flow rate measurements if the variability in the individual variables is known or can be estimated.

3.1.2 Collection of Required Information

If the operating procedures of Section II were followed for a given test, it is assumed that the operational error falls within the limits assumed for the functional analysis (Subsection 4.1). The required information on equipment performance is taken from the calibration log book.

3.1.2.1 Barometer - The barometer has an operational and calibration check before each field test. If the calibration log book shows that the barometer reading is within ± 0.3 percent (about 0.1 inch of mercury) of the reading of the wall barometer before each field test, the performance criterion is being satisfied.

3.1.2.2 Temperature-Measuring System - The temperature readout device is checked and adjusted if necessary before each field test. The temperature measuring system is checked against a mercury thermometer at laboratory conditions before each field test. If the calibration log book shows that the system's reading was within ± 1.5 percent of the mercury thermometer (absolute temperature °R) reading before each field test, the performance criterion for this system is being satisfied.

3.1.2.3 Type-S Pitot Tube - Calibration of the Type-S pitot tube is checked before every third field test or after three months, whichever occurs first. If the conditions as specified in Subsection 3.3.2, How to Monitor Important Variables, are satisfied, the suggested performance criteria are being satisfied. (It may require the collection and analysis of pitot tube calibration data in order to arrive at a valid performance criteria for pitot tube calibrations.)

3.1.3 Treatment of Information

The suggested performance criteria as given in Table 2 of Subsection 3.2 represents 3 CV error limits for equipment calibrations. (Criteria are specified as a percent, i.e., $CV = \sigma\ 100/\mu$ when dealing with population parameters; these are sometimes called coefficients of variation, as is done throughout this document, and sometimes relative standard deviations.) Estimates of the coefficient of variation, CV, for certain operational errors are given in Subsection 4.1 as part of the functional analysis. Using these values, simulation and sensitivity analyses of the measurement process for a gas velocity range of from 6 feet per second to 24 feet per second showed the coefficient of variation to be less than 2.33 percent for all cases. Hence, if the operational procedures are followed and the suggested performance criteria as given in Table 2 are satisfied, a coefficient of variation of 2.33 percent can be assumed as a best estimate.

If it is necessary to change the performance criteria, or if in certain cases one or more of the operational sources of error is (are) assumed to be different than that used in this document, a new coefficient of variation for the measurement process must be calculated using the new variable values. This is accomplished by substituting the new estimated $CV^2\{X\}$ in Table 4, page 46 of Subsection 4.1.1, computing the weighted CV^2, and summing these weighted CV^2. Take the square root and get $CV\{Q_s\}$ for this particular set of conditions.

3.1.4 Reporting Data Quality

The measured volumetric flow rate will be used in conjunction with one of the other methods for measuring a particular pollutant to calculate the average emissions level for that pollutant. When reported as an individual quantity, it should be accompanied with a precision statement. For example, report

$$Q_{sm}\ (1 \pm 3\ CV)$$

where Q_{sm} = the measured value, and

CV = the coefficient of variation.

Performing the operations as given in Section II and satisfying the suggested performance criteria implies that a CV of less than 2.33 percent is applicable to that data. The reported value would be

$$Q_{sm}\ (1 \pm 0.07)$$

The utility of the above statement follows from the fact that if the measured values of Q_s are normally distributed about a mean value $\bar{Q}_s$ and if the team repeated the velocity traverse several times at the same process conditions (if this were possible), approximately 99.7 percent of their measured values, Q_{sm}, would be in the interval of 0.93 $\bar{Q}_s$ to 1.07 $\bar{Q}_s$.

Notice that this statement is about precision only, i.e., how well that particular team can reproduce its measurements if the stack gas velocity profile remains fixed. These measurements could be very inaccurate (biased). To estimate that aspect, another independent measure is required (see Subsection 4.2, page 49).

3.2 SUGGESTED PERFORMANCE CRITERIA

Data assessment as discussed in the previous subsection was based on the premise that all variables are controlled at a given level. These levels or suggested performance criteria are the values given in the Operations Manual for determining when to recalibrate the Type-S pitot tube or when to adjust the temperature-measuring system or the barometer. Criteria for judging performance are summarized in Table 2.

3.3 COLLECTION AND ANALYSIS OF INFORMATION TO IDENTIFY TROUBLE

In a quality assurance program, one of the most effective means of preventing trouble is to respond immediately to indications of suspicious data or equipment malfunctions. There are certain visual and operational checks that can be performed while the measurements are being made to help assure the collection of data of good quality. These checks are written as part of the routine operating procedures in Section II. Generally, equipment malfunctions, unless they are of major proportions, are not discovered until after the test. The term "applying quick corrective actions" in this case will generally imply that the malfunction is discovered and corrected before attempting another field test. In order to effectively apply preventive-type maintenance procedures to the measurement process, the supervisor must know the important variables in the process, know how to monitor the critical variables, and know how to interpret the data obtained from monitoring operations. These subjects are discussed in the following subsections.

3.3.1 Identification of Important Variables

Determination of the volumetric flow rate requires a sequence of operations and measurements that yields as an end result a number that serves to represent the average volumetric flow rate. There is no way of knowing the accuracy, i.e., the agreement between the measured and the true value, for a given field test. However, a knowledge of the important variables and their characteristics allows for the application of quality control procedures to control the effect of each variable at a given level during the field test, thus providing a certain degree of confidence in the validity and accuracy of the final result.

Table 2: SUGGESTED PERFORMANCE CRITERIA

Criteria for Recalibrating/Adjusting Equipment		
1.	Type-S Pitot Tube	$D_c^* \geq \pm 1.2\%$
2.	Temperature Measuring System	$D_T^\dagger \geq \pm 1.5\%$ at 730°R
3.	Barometer	$D_b^\# \geq \pm 0.3\%$ at 29.92 inches of mercury
Criteria for Performing Calibration Checks		
4.	Type-S Pitot Tube	Perform a three-point calibration check every third field test or every three months, whichever occurs first.
5.	Temperature Measuring System	Perform a one-point check at room temperature before each field test.
6.	Barometer	Perform a one-point check at barometric pressure against a mercury barometer before each field test.

*D_c is the percent difference in a new calibration point and the current calibration curve.

†D_T is the percent difference in the absolute ambient temperature expressed in °R as measured by the temperature measuring system and that measured by a mercury bulb thermometer.

#D_b is the percent difference in barometric pressure in inches of mercury as measured by the field barometer and a mercury barometer.

A functional analysis of this method of measuring stack gas velocity was made to identify the important variables (see Subsection 4.1). Also, a laboratory and field evaluation has been performed to assess the variability of the method under fixed conditions (Ref. 4). The error values used here are intended to be representative of what a qualified and conscientious field team could maintain under normal field conditions over a long period of time. Results from the functional analysis and the above evaluation, combined with engineering judgment, in some instances, are used in the following discussion of important variables. Under normal operation, parameters can be ordered according to their decreasing contribution to variability in the measured volumetric flow rate as follows:

(1) $(\sqrt{\Delta P})_{avg}$, the average of the square roots of the velocity pressure head measurements for a velocity traverse,

(2) C_p, the Type-S pitot tube coefficient,

(3) A, stack cross sectional area,

(4) $\sqrt{(T_s)_{avg}}$, square root of the average stack gas temperature,

(5) P_s, absolute stack gas pressure,

(6) M_s, molecular weight of stack gas (wet basis), and

(7) B_{wo}, proportion by volume of water vapor in the gas stream.

A brief description of the assumptions made and the techniques used in the functional analysis is given in Subsection 4.1 of this document. A more comprehensive treatment is given in the final report for this contract. The source and magnitude of uncertainty for each of the above parameters are discussed below.

3.3.1.1 <u>Type-S Pitot Tube Coefficient, C_p</u> - The Type-S pitot tube coefficient, C_p, is determined by calibration against a standard pitot tube or an NBS-calibrated Type-S pitot tube. Uncertainty in C_p then is a combination of the uncertainty in the coefficient of the reference pitot tube, i.e., the standard pitot tube or the NBS-calibrated Type-S pitot tube, and the uncertainty in the calibration technique.

In practice, standard pitot tubes are seldom calibrated. A standard tube is assumed to have a coefficient of 0.99 ± 0.01 over the velocity range encountered in source testing. If the directions given in Subsection 2.1.2.1 are followed when calibrating a Type-S pitot tube, it is estimated that the maximum error (i.e., ± 3 CV) in the coefficient of the reference pitot tube will be about ± 1 percent over the velocity pressure range from about 0.10 to 10 inches of water.

Uncertainty in the calibration technique on an intra-laboratory basis is not known. Coefficients of Type-S pitot tubes ranging from 0.82 to 0.9 have been reported in the various literature. It is not conclusive whether this range represents the actual difference in Type-S pitot tubes or is partially, at least, due to poor calibration technique. It is felt by some people experience in calibrating pitot tubes that a well-manufactured Type-S pitot tube will have a coefficient of 0.85 ± 0.02 (Ref. 1). However, C_p values well outside this range have been reported for Type-S pitot tubes in recent publications (Ref. 4). From these sparse data, it would appear that an error of 3 or 4 percent would not be uncommon for a pitot tube coefficient. Uncertainty in the coefficients of a standard pitot tubes would be a part of the uncertainty in the Type-S pitot tube coefficient.

It is felt that to effectively minimize this source of error, all new Type-S pitot tubes should be calibrated before use in the field. Also, the pitot tube should be visually checked for damage before and after each field test. The calibration should be checked at any sign of damage, or every third field test or every three months, whichever occurs first, as a guard against continued performance of field tests with a damaged pitot tube. This calibration schedule should be decreased if the data show that there is no degradation of the calibration with time and that any damage sufficient to change the calibration can be visually detected.

3.3.1.2 Velocity Head Pressure, ΔP - Error in measuring the differential pressure, ΔP, can result from error in reading the inclined manometer and from poor alignment of the pitot tube along its roll and pitch axes. Also, for a specific traverse point the measured ΔP can be in error because of an improperly positioned pitot tube if the stack gas velocity varies with position. An additional source of error occurs when pulsating pressures are visually averaged. The characteristics of each of the error sources are discussed separately in the following paragraphs.

It is generally assumed that an inclined manometer can be read to within ± 1/2 of its smallest division. An estimated maximum reading error of ± 10 percent was made for an inclined manometer with divisions of 0.01 inches of water and for ΔP's equal to or greater than 0.05 inches of water (Ref. 6). Pure reading errors tend to be of a random nature and normally distributed about a mean value of zero. For the adverse conditions frequently encountered in the field, it seems reasonable to take 1 division or $\pm$ 20 percent as the maximum reading error. Assuming this maximum error to be representative of the 3 CV limits, the resulting coefficient of variation which is the standard deviation expressed as a percent, i.e., $CV = \sigma \times 100/\mu$, would be 20/3 or 6.67 percent.

From Figure 2, page 12 it can be seen that a maximum error of about + 5 percent will occur from poor alignment of the pitot tube along its roll axis for angles less than $\pm$ 40 degrees. This error then results in a positive bias of the measured value. The bias would be expected to be random in nature.

Figure 3, page 12 shows that error due to the pitot tube alignment along its pitch axis can be positive or negative. If a misalignment of $\pm$ 20 degrees is about the maximum that would occur under normal conditions, the error would range from a + 7.5 percent to a - 11 percent. This error can be roughly modeled as a normal distribution with a zero mean and a CV of 3.0 percent.

For pulsating flows that are averaged visually, a positive error results. The magnitude of the error is a function of the pulse width and the average ΔP being measured. Visual averaging gives the arithmetic average, which gives $\sqrt{\Delta P_{avg}}$ when the square root is taken, whereas the correct and desired value is $(\sqrt{\Delta P})_{avg}$. Figure 6 graphically illustrates the error that would result from visual averaging of four different pulse widths as a function of ΔP. It can be seen from the figure that an approximate 4 percent error occurs when the pulse width is equal to the ΔP being measured. The error rises sharply for pulse widths greater than the ΔP being measured and drop off slowly for pulse widths less than the ΔP being measured. In cases where the pulses are approximately symmetrical about the average, correct results can be obtained by recording the pulse extremes, taking the square root of both extremes, and averaging. Non-symmetrical pulses are more difficult, and visual averaging may be the only practical procedure to use at this time. This error would tend to be relatively constant throughout a given field test but random over several tests.

An exact combining of the above errors would be complex. However, for this purpose it is felt that the combined errors can be adequately enveloped when modeled as a normal probability distribution with a mean value of + 2 percent and a standard deviation of 12 percent. This is the error associated with individual ΔP measurements. The resulting influence on the average stack gas velocity and/or volumetric flow rate is considerably less because of the functionsl relationship between $(V_s)_{avg}$ or Q_s and ΔP. For example, if the measured values ΔP_m, of a constant ΔP are normally distributed with a relative bias of + 2 percent and a coefficient of variation of 12 percent, then $\sqrt{\Delta P_m}$ will be normally distributed with a relative bias

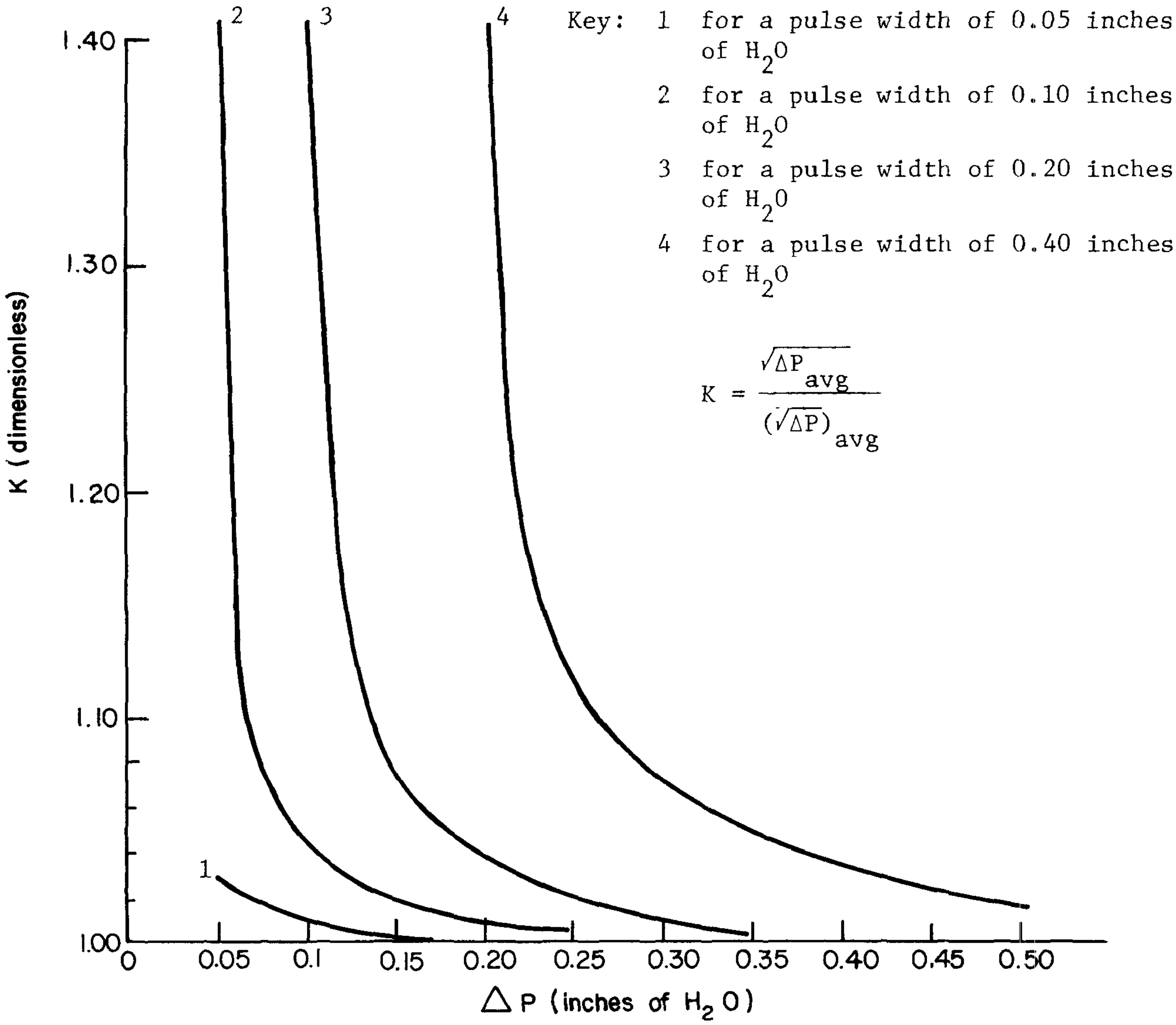


Figure 6. Potential Bias in $\sqrt{\Delta P}$ for Pulsating Flow as a Function of Pulse Width and ΔP.

of ± 1 percent and a coefficient of variation of 6 percent. Furthermore $(\sqrt{\Delta P})_{avg}$ for 12 traverse points would be normally distributed with a relative bias of + 1 percent and a coefficient of variation of $6/\sqrt{12}$ or 1.7 percent. It is this much smaller variability that is reflected in the measured average velocity and volumetric flow rate.

A CV of 1.7 percent for the $(\sqrt{\Delta P})_{avg}$ seems to be in agreement with the results of a laboratory and field evaluation of Method 2 (Ref. 4). In this evaluation CV's were calculated for two velocity levels from five replicates at the lower velocity and four replicates at the higher velocity. The results were a CV of 1.95 percent for the low velocity and a CV of 2.15 percent at the higher velocity. For such a small number of replicates the two values are not significantly different. Variability in the evaluation data contains not only that characteristic of short-term repeatability of the method but also that due to the inability to maintain/reproduce a given velocity profile at the sampling site by controlling process conditions over a period of time (the replicates were performed over a two-day period). These values then could be larger or smaller than the true long-term reproducibility of the method according to the magnitude of the variability in reproducing the velocity profile.

In any one given field test, there can be a significant bias in the measurement if the errors are not random, for example, if the ΔP's are consistently read high or low due to parallax error or if the pitot tube is consistently misaligned in the same direction on its pitch or roll axis throughout the test. The average bias in determining ΔP or aligning the probe along its roll axis is reduced by taking the square root only and is not reduced by averaging the 12 values. In general the $(\sqrt{\Delta P})_{avg}$ values will be biased high as a result of the two positive biases discussed above.

3.3.1.3 Stack Cross Sectional Area, A - Any error in the measured cross-sectional area is directly reflected in the measured volumetric flow rate. On large out-of-round stacks or on stacks with irregular inner walls, it is difficult to determine the stack's average diameter from one measurement. Also, any error in the measured diameter appears double in the area (see Subsection 4.1.3). There are no data available, and this is only a guess; but it seems reasonable to use a coefficient of variation of 0.5 percent for determining the average diameter of a stack. This then would result in a coefficient of variation of 1 percent in the calculated area.

A more valid error estimate can be obtained by evaluating the stack cross-section data from different field tests as recorded on the form in Figure 5 of Section II. If the diameter was measured from two or more sampling ports, compare the areas that would have been obtained from the individual measurements to that obtained from the average of all of the measurements. Also, when time permits and especially on stacks on which it is difficult to make diameter measurements, it might prove valuable to compare the stack area derived from diameter measurements with that obtained from a circumference measurement. In either case, if the difference is consistently larger than about 1 percent of the average area, the stack area should continue to be obtained from the average of the diameters measured from all the available sampling ports and, if warranted and practical, from the average of the diameter and circumference measurements.

3.3.1.4 Average Stack Gas Temperature, $(T_s)_{avg}$ - For a specific field test the error in stack gas temperature will probably have a small random component and a larger constant component. The random component is further reduced by averaging over 12 measurements (if the temperature is measured at each traverse point). Also, since $(V_s)_{avg}$ and Q_s are functions of $\sqrt{(T_s)_{avg}}$ and $1/\sqrt{(T_s)_{avg}}$, respectively, as given in equations 2-2 and 2-3 of Appendix A, the influence of the constant component is reduced by half. For example, if the measured average temperature is within $\pm$ 1.5 percent of its true absolute value (the reference method requires this accuracy at the minimum absolute temperature of the stack gas), the resulting error in $(V_s)_{avg}$ and Q_s would be 0.75 percent. Therefore, it is important to check the stack gas temperature-measuring system against other available temperature-measuring devices periodically throughout the field test to guard against malfunctions resulting in a large constant error in the temperature measurements. Effects of the random component of system error should seldom be as significant as the constant (bias) component. A CV of about 1.0 percent was derived from repeated measurements of $(T_s)_{avg}$ over a two-day period (Ref. 4). These values include short-term repeatability of the method plus variability in maintaining/reproducing the same temperature profile over a period of time. Although the above is not a measure of the reproducibility of the temperature-measuring system, it is felt that if the directions as given in Section II are followed, a CV of 1.0 percent can serve as a best estimate of reproducibility until more applicable data become available. It should be pointed out here that if T_s varies by more than about 10 percent of the mean from point to point in the stack, the correct term to use is $(\sqrt{T_s})_{avg}$ rather than $\sqrt{(T_s)_{avg}}$.

3.3.1.5 Absolute Stack Gas Pressure, P_s - It has been estimated that the maximum error in measuring P_s, under normal conditions, is about 0.47 percent (Ref. 6). However since P_s can vary during a field test, a maximum error in determing the true average P_s that should be used in subsequent calculations is assumed to be larger than 0.47. A value of 0.9 percent is used in this document. It is a rough estimate and not based on actual data. $(V_s)_{avg}$ and Q_s are functions of $1/\sqrt{P_s}$ and $\sqrt{P_s}$, respectively. Therefore, only one-half of the error in P_s appears in $(V_s)_{avg}$ and Q_s.

3.3.1.6 Molecular Weight of the Stack Gas (Wet Basis), M_s - The stack gas molecular weight on a dry basis is determined by Method 3. It is converted to a wet basis using the results of Method 4. A more thorough error analysis will be performed in the development of a Quality Assurance Document for those methods. Error in determining M_s should be insignificant when calculating $(V_s)_{avg}$ and Q_s. However, the error in determining the CO_2 content of the gas becomes significant and critical when used in conjunction with Method 5 in correcting emissions levels to 12 percent CO_2 as is required for incinerators. This problem will be discussed in the Quality Assurance Documents 3, 4, and 5.

3.3.1.7 Moisture Content of Stack Gas by Volume, B_{wo} - The stack gas moisture content is determined by Method 4. A more thorough error analysis will be performed in developing a Quality Assurance Document for Method 4. For this document, it was assumed that under normal operating conditions the maximum error of interest in calculating Q_s would not exceed 1 percent (Ref. 6). That is

$$\frac{E(B_{wo})}{1 - B_{wo}} \leq 0.01$$

where $E(B_{wo})$ = error in measuring the moisture content, and

$1 - B_{wo}$ = term as it appears in the Q_s equation.

3.3.2 How to Monitor Important Variables

In general, if the procedures outlined in the Operations Manual are followed, the major sources of error will be under control. It is felt, however, that error sources associated with determining C_p, ΔP, T_s, and A are important enough to warrant some form of special monitoring. Each parameter is discussed separately.

3.3.2.1 Type-S Pitot Tube Calibration - Pitot tube calibration error is directly reflected in the velocity or flow rate measurement. Since it is not known with certainty if there is actually a large variation in C_p for different Type-S pitot tubes, or if the variability is due to poor calibration technique, it is suggested that a quality control chart be maintained to aid in detecting any variability and to identify the source of variability. Construction and maintenance of quality control charts are discussed in References 7, 8, and 9.

A sequential plotting of the C_p values derived from each calibration check is recommended for monitoring the pitot tube calibration. Figure 7 is a sample control chart with the center line and the $\pm$ 2 CV and $\pm$ 3 CV lines and sample data points drawn in. The coefficient of variation is assumed as 0.4 percent. (As laboratory data become available, this assumption should be evaluated and adjusted as necessary).

For each calibration check compute the percent difference, D_c, in the check value, C_{pc}, and the original value, C_{po}, as obtained from the calibration curve at the ΔP being checked by

$$D_c = \frac{C_{pc} - C_{po}}{C_{po}} \times 100.$$

Plot the D_c values as they are obtained. The abscissa identifies the points chronologically, e.g., numbers them in order starting with 1.

The chart should be studied after each calibration check to see if:

(1) any point is outside the $\pm$ 3 CV limits,

(2) two consecutive points are outside the $\pm$ 2 CV limits,

(3) a trend is developing, e.g., four or more consecutive points show a monotonic trend away from the mean, or

(4) there is a bias in the calibration system as indicated by seven or more consecutive points on the same side of the center line.

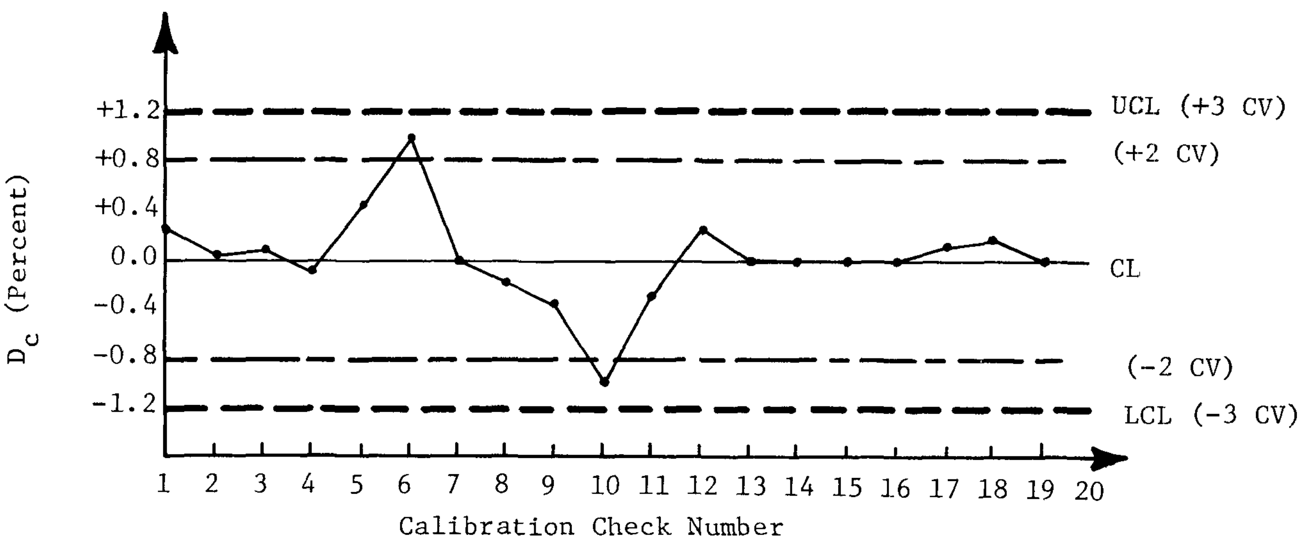


Figure 7. Sample Control Chart for Pitot Tube Calibration Checks.

The cause should be determined and corrective action taken if any of the above situations are observed. Corrective actions could be taken in the form of a complete recalibration of the Type-S pitot tube, replacing the pitot tube with a new tube, or instructing the team members in correct calibration procedures.

3.3.2.2 Velocity Pressure Head, ΔP - Velocity pressure head measurements can be effectively monitored by the supervisor during the actual test by making periodic checks on probe alignment, probe positioning, and inclined manometer readings.

Probe alignment can easily be checked when the equipment is first set up at a sampling port. With the pitot tube inserted in the sampling port, a small, pocket-size bubble level could be used by the supervisor or one of the team members to check the probe alignment along the pitch and roll axes. Adjustments can be made in the sampling train supports if the probe is out of alignment.

Probe positioning is monitored by observing the pitot tube markings as indices and visually checking to see if the pitot tube is directed straight into the sampling port.

To guard against a constant bias in the inclined manometer readings, team members could be rotated periodically during the test; and if possible, in cases where the pressure has short-term pulses that are of the same order of magnitude as the average ΔP being measured, read the high and low values, take the square roots, then average for the $\sqrt{\Delta P}$ value at that traverse point.

3.3.2.3 Stack Gas Temperature, T_s - Temperature-measuring systems are subject to frequent malfunctions. Some systems are sensitive to changes in power line voltage and to r-f electromagnetic fields. One easy way of checking the system is to have a long-stemmed dial thermometer and measure stack gas temperature at the same point in the stack. This could be done before a test is started and any time the stack gas temperature appears to change abruptly during the test.

3.3.2.4 Determining the Stack Area, A - Error in determining the average diameter of a stack appears double in the area and subsequently in the volumetric flow rate value. A quick check on this could be to have two different team members measure the diameter at different times during the test and use the average.

SECTION IV MANUAL FOR MANAGER OF GROUPS OF FIELD TEAMS

4.0 GENERAL

The guidelines for managing quality assurance programs for use with Test Method 2 - Determination of Stack Gas Velocity and Volumetric Flow Rate (Type-S Pitot Tube) are given in this part of the field document. This information is written for the manager of several teams for measuring source emissions and for the appropriate EPA, State, or Federal Administrators of these programs. It is emphasized that if the analyst carefully adheres to the operational procedures and checks of Section II, then the errors and/or variations in the measured velocities should be consistent with the performance criteria as suggested. Consequently, the auditing routines given in this section provide a means of determining whether the stack sampling test teams of several companies are following the suggested procedures. The audit function is primarily one of independently obtaining measurements and performing calculations where this can be done. The purpose of these guidelines is to:

(1) present information relative to the test method (a functional analysis) to identify the important operations and factors,

(2) present a data quality audit procedure for use in checking adherence to test methods and validating that performance criteria are being satisfied, and

(3) present the statistical properties of the auditing procedure in order that the appropriate plan of action may be selected to yield an acceptable level of risk to be associated with the reported results.

These three purposes will be discussed in the order stated in the sections which follow. The first section will contain a functional analysis of the test method with the objective of identifying the most important factors which affect the quality of the reported data and of estimating the expected variation and biases in the measurements resulting from equipment and operator errors.

There are no absolute standards with which to compare the routinely derived measurements. Furthermore, the taking of completely independent measurements at the same time that the routine data are being collected (e.g., by introducing two pitot tubes into the stack at the same time) is not considered practical due to the constrained environmental and space conditions under which the data are being collected. Hence, a data quality audit procedure is recommended as one means of independently checking on the source emissions data.

The second section contains a description of a data quality audit procedure. The most important variables identified in Section 4.1 are considered in the audit. The procedure involves the random sampling of n stacks from N = 20 stacks (or from the stacks tested during a three-month period, whichever occurs first) for which one firm is conducting the source emissions tests. For each of the stacks selected, independent measurements will be made of the indicated variables. These measurements will be used in conjunction with the routinely collected data to estimate the quality of the data being collected by the field teams.

The data quality audit procedure is an independent check of data collection and analysis techniques with respect to the important variables. It provides a means of assessing data collected by several teams and/or firms with the potential of identifying biases/excessive variation in the data collection procedures. The independent auditor should be able to assist some field teams in improving their measurement procedures through his knowledge of the measurement process and through information gained from other field teams currently collecting precise and accurate data.

The statistical sampling and test procedure recommended is sampling by variables. This procedure is described in Section 4.3. It makes maximum use of the data collected, and it is particularly adaptable to the small lot size and consequently the small sample size applications. The same sampling plans can be employed in the quality checks performed by a team or firm in its own operations. The objectives of the sampling and test procedure are to characterize data quality for the user and to identify potential sources of trouble in the data collection process for the purpose of correcting the deficiencies in data quality.

4.1 FUNCTIONAL ANALYSIS OF TEST METHOD

Test Method 2 - Determination of Stack Gas Velocity and Volumetric Flow Rate (Type-S Pitot Tube) is described in the Federal Register of December 23, 1971 and given in Appendix A. The stack gas velocity is given by

$$(1) \qquad \left(V_s\right)_{avg} = K_p C_p \left(\sqrt{\Delta p}\right)_{avg} \sqrt{\frac{\left(T_s\right)_{avg}}{P_s M_s}}$$

where $\left(V_s\right)_{avg}$ = stack gas velocity, feet per second (f.p.s.),

$K_p = 85.48 \frac{ft}{sec} \left(\frac{lb.}{lb.mole-°R}\right)^{1/2}$ when these units are used,

C_p = pitot tube coefficient, dimensionless,

$\left(T_s\right)_{avg}$ = average absolute stack gas temperature, °R,

$(\sqrt{\Delta P})_{avg}$ = average of square roots of velocity heads (in of $H_2O)^{1/2}$,

P_s = absolute stack gas pressure, inches Hg,

M_s = molecular weight of stack gas (wet basis), lb./lb.-mole. $M_d\ (1 - B_{wo}) + 18\ B_{wo}$,

M_d = dry molecular weight of stack gas (from Method 3),

and B_{wo} = proportion by volume of water vapor in the gas stream (from Method 4).

The volumetric flow rate is given by

$$(2) \qquad Q_s = 3600\left(1 - B_{wo}\right)\left(V_s\right)_{avg} A \left(\frac{T_{std}}{\left(T_s\right)_{avg}}\right)\left(\frac{P_s}{P_{std}}\right)$$

where Q_s = volumetric flow rate, dry basis, standard conditions, ft^3/hr,

A = cross-sectional area of stack, ft^2,

T_{std} = absolute temperature at standard conditions, 530°R, and

P_{std} = absolute pressure at standard conditions, 29.92 inches Hg.

Note that in equation 2-3 of Appendix A the term V_s is used. This should be $(V_s)_{avg}$ as calculated by equation 2-2.

4.1.1 Variance Analysis

An analysis is now made of these two equations to relate the errors of analysis of the individual factors to those in V_s and Q_s. The analysis can be done manually using the fact that the functional relationshps are of a product form. This straightforward analysis can be performed by the contractor conducting the source emissions test.

This is a standard error analysis of the relationships using methods of calculus. The methodology is presented in the Final Report on this contract; only the application of the results will be described herein. Estimates of the mean (or nominal) value and standard deviation of each variable are required. Estimates of the corresponding mean and standard deviation of the stack gas velocity and volumetric flow are then determined. Because of the multiplicative forms of equations (1) and (2), the relative error in V_s is obtained through the use of equation (3) below.

In performing a variance analysis, the ratio of the variance of the measurement divided by the square of the mean value, i.e., the square of the coefficient of variation (CV) of the measurement, is used. The CV or relative standard deviation of a measurement X is defined as the ratio of the standard deviation of X and the mean of X expressed in percent; i.e., $CV\{X\} = 100\ \sigma_X/\mu_X$. This quantity is estimated by $\widehat{CV}\{X\} = 100\ s_X/\bar{X}$ where s_X is the computed standard deviation and $\bar{X}$ is the mean or average of the measurements. For example, if the stack gas pressure can be read to within 0.15 inches of Hg and the mean value is 29.54 inches, then the coefficient of variation is approximately 0.25 percent, or 0.0025, if it is assumed that reading errors are normally distributed and that 0.15 represents the 2σ value. Similarly each variable can be analyzed and its coefficient of variation determined.

The following relationship between the coefficients of variation is obtained, assuming no correlation in the errors of the variables,

$$(3)\quad CV^2\left\{\left(V_s\right)_{avg}\right\} = CV^2\left\{C_p\right\} + CV^2\left\{\left(\sqrt{\Delta P}\right)_{avg}\right\} + 1/4\ CV^2\left\{\left(T_s\right)_{avg}\right\} + 1/4\ CV^2\left\{P_s\right\} + 1/4\ CV^2\left\{M_s\right\}$$

The coefficient, 1/4, for the last three terms results from the square of the exponent, 1/2, of equation (1). The estimated CV's are denoted by $\widehat{CV}\{X\}$, where X denotes the variable.

The results of the variance analysis for V_s are tabulated in Table 3.

Table 3. VARIANCE ANALYSIS OF $(V_s)_{avg}$

Variable (X)	Estimated $CV^2\{X\}$	×	Weighting Coefficient	=	Weighted $\widehat{CV}^2\{X\}$
C_p	1.00		1		1.00
$\left(\sqrt{\Delta P}\right)_{avg}$	2.89		1		2.89
$\left(T_s\right)_{avg}$	1.00		0.25		0.25
P_s	0.09		0.25		0.023
M_s	0.5		0.25		0.125
$\left(V_s\right)_{avg}$				$\widehat{CV}^2\left\{V_s\right\}$ =	4.29
				$\widehat{CV}\left\{V_s\right\}$ =	2.07%

For example, $CV\{P_s\}$ = 0.30 percent, $CV^2\{P_s\}$ = 0.09. The individual CV's are then combined using the weighting coefficients given by equation (3) to obtain the estimated $CV\{V_s\}$ as 2.07 percent. Errors exceeding 4.14 percent (2 × 2.07%) would be expected to occur about 5 percent of the time, greater than 6.21 percent less than one percent of the time, using the percentiles of the normal distribution.

The estimated coefficient of variation for each variable is based on a combination of data in References (1, 3, 4, and 10) where available. Specific methods for estimating CV using available data are to be given in the final report on this contract. Otherwise, estimates are based on engineering judgments concerning reading errors, pitot tube alignment errors, etc., see subsection 3.3, page 29. It is important to realize that as a rule results of special tests and analyses as reported in the references are not directly applicable to this analysis, but they do provide ranges and limits from which reasonable estimates can be made. For example, error estimates as given in references 6 and 10 are usually in terms of equipment capability when properly maintained and calibrated. Such estimates probably represent the best that can be achieved over short time intervals in source testing. Somewhat larger values are employed here to represent what a qualified and conscientious field team can be expected to achieve over a long period of time. Also, results of a laboratory and field evaluation of the method in which replicate measurements were made (Ref. 4) are not directly applicable since, for example, the variability in the measured average velocity contains not only the intra-team variability of the measurement method but also the ability to reproduce from day to day a stack gas velocity profile at the sampling site by reproducing process conditions such as fuel feed rate. The term "estimate" as used here is also applicable to measured values as reported in Reference 4 where only four or five replicates were made and a sample average, $\bar{X}$, and sample standard deviation, s, calculated. These calculated sample statistics are estimates of the population parameters μ and σ, respectively. For example, if s is calculated from a sample of size 4, the resulting 95 percent confidence interval for the population standard deviation (assuming the population is normally distributed), is approximately $0.57s \leq \sigma \leq 3.7s$.

Certain assumptions are made in the variance analysis which are to be discussed in the final report on this project. (Also see Final Report on Contract EPA-Durham 68-02-0598.)

Combining equations (1) and (2), equation (4) is obtained for Q_s. This equation is used to obtain the variance estimates for Q_s as given in Table 4.

$$(4) \qquad Q_s = 5.45 \times 10^6 \, (1 - B_{wo}) \, A \, C_p \left(\sqrt{\Delta P}\right)_{avg} \left[\frac{P_s}{M_s \left(T_s\right)_{avg}}\right]^{1/2}$$

As a result of these analyses, the variables C_p and $(\sqrt{\Delta P})_{avg}$ are considered as the most important ones for inclusion in an auditing procedure. Including only these two variables results in a $CV\{Q_s\} = (3.89)^{1/2} = 1.97$ percent compared to 2.33 percent obtained using all of the variables. These two variables then account for over 85 percent of the total variability in Q_s. Therefore, actions for improving data quality should be directed toward these two variables. Of course, it is important to determine the cross-sectional area as precisely as possible since it, too, can significantly affect the results. The area was not included in the audit because a specific dimension measurement can be made quite accurately; it is the use of this specific measurement as an estimate of the average dimension that results in error, and auditing would not necessarily detect this particular error.

Table 4. VARIANCE ANALYSIS FOR Q_s

Variable	Estimated $\widehat{CV}^2\{X\}$	×	Weighting Coefficient	=	Weighted $\widehat{CV}^2\{X\}$
$1 - B_{wo}$	0.09		1.38*		0.13
C_p	1.00		1.0		1.00
A	1.00		1.0		1.00
P_s	0.09		0.25		0.02
$\left(\sqrt{\Delta P}\right)_{avg}$	2.89		1.00		2.89
$\left(T_s\right)_{avg}$	1.0		0.25		0.250
M_s	0.50		0.25		0.125
Q_s					$\widehat{CV}^2\{Q_s\}$ = 5.42 $\widehat{CV}\{Q_s\}$ = 2.33%

*The weighting coefficient for $1 - B_{wo}$ is $1/(1 - B_{wo})^2$, assuming B_{wo} to be 0.15, this yields $1/(0.85)^2 = 1.38$.

4.1.2 Bias Estimation

A reasonably simple method is given below of estimating the bias in a measurement, such as stack gas volumetric flow rate, which is expressed as a function of several other variables, the measurement of which may be biased. In order to illustrate the method, consider first a simpler but similar form of the equation and then apply the method to the stack gas volumetric flow measurement. Suppose that the measurement, Y, is related to variables, X and W, through the equation

$$Y = KX\sqrt{W}\ , \qquad K \text{ a constant.}$$

Assume that the measured values of X and W have both a bias and a random error associated with them, i.e.,

$$X \text{ (measured)} = X_M = X_T + \tau_X + \varepsilon_X$$

$$= \text{true or correct value} + \text{bias} + \text{random error.}$$

Similarly let

$$W \text{ (measured)} = W_M = W_T + \tau_W + \varepsilon_W\ .$$

It is assumed that the random errors ε_X and ε_W have zero means.

Substitute these values for X and W in the first equation to estimate the bias in the measured or calculated Y from measured values of X and W.

$$Y \text{ (Calculated)} = K\ (X_T + \tau_X + \varepsilon_X)\ \sqrt{(W_T + \tau_W + \varepsilon_W)}$$

$$= K\ X_T \sqrt{W_T}\ \left(1 + \frac{\tau_X}{X_T} + \frac{\varepsilon_X}{X_T}\right)\sqrt{1 + \frac{\tau_W}{W_T} + \frac{\varepsilon_W}{W_T}}\ \ .$$

The square root of 1 + e where e is small, say $e \leq 0.10$, is given very closely by 1 + 1/2 e. Making this substitution, the equation for Y (calculated) becomes

$$Y(\text{Calculated}) \cong K\, X_T \sqrt{W_T}\left(1 + \frac{\tau_X}{X_T} + \frac{\varepsilon_X}{X_T}\right)\left(1 + 1/2\ \frac{\tau_W}{W_T} + 1/2\ \frac{\varepsilon_W}{W_T}\right).$$

Denote Y_T (true value) = $K\, X_T \sqrt{W_T}$, then

$$Y(\text{Calculated}) \simeq Y_T \left(1 + \frac{\tau_X}{X_T} + 1/2\ \frac{\tau_W}{W_T}\right)$$

The terms involving ε_X and ε_W will be zero on the average, as they are the random errors. Thus, the bias in Y is given by the sum of the relative bias of the X's and one-half that for the W's (the effect of the square root). This simple example illustrates how the bias in the values of V_s and Q_s can be obtained. The computational form given in Table 5 indicates the procedure for Q_s. All biases are taken as zero; i.e., all error terms are normally distributed with a zero mean except C_p and $(\sqrt{\Delta P})_{avg}$. The bias in $(\sqrt{\Delta P})_{avg}$ is discussed on page 32. A token negative bias of -0.005 is used for C_p since any misalignment along the roll axis of the Type-S pitot tube (see Figure 2, page 12) during calibration gives a higher-than-true ΔP_{test}.

Table 5. COMPUTATION OF BIAS IN Q_s

Variable	Relative Bias*	Weighting Coefficient	Weighted Relative Bias (B)
$1 - B_{wo}$	0	- .18	0
A	0	1	0
C_p	-.005	1	-.005
$(\sqrt{\Delta P})_{avg}$	.01	1	.01
P_s	0	1/2	0
M_s	0	1/2	0
$(T_s)_{avg}$	0	1/2	0
Q_s			+0.005

*Relative Bias = $\frac{\text{Absolute Bias}}{\text{True Value}}$

The relative bias in Q_s is given by 0.005, or 0.5 percent; i.e., the values of Q_s would on the average be about 0.5 percent high. The values used in this table are rough estimates and used only for illustration; actual biases should be based on collected data and analysis of the measurement technique.

4.2 PROCEDURES FOR PERFORMING A QUALITY AUDIT

"Quality audit" as used here implies a comprehensive system of planned and periodic audits to verify compliance with all aspects of the quality assurance program. Results from the quality audit provide an independent assessment of data quality. "Independent" means that the individuals performing and some of the equipment used in the audit are different from the regular field crew and equipment. From these data both bias and precision estimates can be made.

The auditor, i.e., the individual performing the audit, should have extensive background experience in source sampling, specifically with the characterization technique that he is auditing. He should be able to establish and maintain good rapport with field crews.

The functions of the auditor are summarized in the following list:

(1) Observe procedures and techniques of the field team during on-site measurements.

(2) Record necessary on-site data to allow for an independent determination of final results.

(3) Check/verify applicable equipment calibrations in the field team's home laboratory.

(4) Verify the presence and operability of required equipment in the field team's home laboratory.

(5) Perform calculations using data obtained from the audit.

(6) Compare the audit value with the field team's test value.

(7) Inform the field team of the comparison results specifying any area(s) that need special attention or improvement.

(8) File the records and forward the comparison results with appropriate comments to the manager.

4.2.1 Frequency of Audit

The optimum frequency of audit is a function of certain costs and desired level of confidence in the data quality assessment. A methodology for determining the optimum frequency using relevant costs is presented in the final report of this contract. Costs will vary between field teams and types of field tests. Therefore, the most cost effective auditing level will have to be derived using relevant local cost data according to the procedure given in the final report on this contract.

4.2.2 Collecting On-Site Information

While on-site, the auditor should observe the field team's overall performance of the field test. Specific operations to observe should include, but not be limited to:

(1) Determining stack dimensions and selecting the number and position of traverse points.

(2) Staying at each traverse point long enough for the system to stabilize.

(3) Marking the pitot tube to insure measurements at the correct traverse points.

(4) Aligning the pitot tube properly along its roll and pitch axes throughout the velocity traverse.

(5) Clearing the pitot tube frequently when measuring in a dust laden gas.

(6) Proper handling and positioning of the pitot tube during the velocity traverse.

(7) Measuring the stack gas static pressure.

The above observations, plus any others that the auditor feels are important, can be used in combination to make an overall evaluation of the team's proficiency in carrying out this portion of the field test. This evaluation will be combined with the results that can be objectively evaluated for an overall proficiency rating of the team for this audit.

Having observed the operations, it is felt that the auditor can just make a duplicate of the data recorded on the form in Figure 2 (this could be done after returning to the base laboratory) with the exception of the ΔP values. It is suggested that the auditor have his own inclined manometer, pitot lines, and a quick-disconnect T-joint. By inserting the T-joint at one of the quick disconnects of the field team's setup, two manometers can be used in parallel and can be physically separated during the test. This independent check is suggested to determine if the error in reading the inclined manometer is random, in which case its effect will be small, or constant, in which case its effect could be much larger than that assumed in the functional analysis. If after several audits the distribution of of the difference in $(\sqrt{\Delta P})_{avg}$ as obtained by the auditor and that obtained by the field team has a zero mean and a coefficient of variation of 1 percent or less, this audit check could be discontinued with no ill effects on the quality of the data.

The audit and the field team's values of $(\sqrt{\Delta P})_{avg}$ should be calculated and compared after the velocity traverse has been completed. If the field team's value varies more than $\pm$ 7.2 percent from the audit value, the field team should check its inclined manometer and reading technique and repeat the traverse. The difference on the first traverse is reported as the audit result for subsequent use in data assessment (Subsection 4.3).

4.2.3 Collecting Laboratory Information

When visiting the field team's home laboratory the auditor should check the calibration log book for the calibration schedule being followed and for previous calibration data. From the previous calibration data he should determine if the field team's equipment has or has not been meeting suggested performance criteria (see Table 2).

Because of the uncertainty of the calibration technique for Type-S pitot tubes, it is recommended that the auditor have as part of his equipment an NBS-calibrated standard pitot tube for independently determining the coefficient of the field team's Type-S pitot tube.

The auditor should follow the procedures given in Section II for calibrating the Type-S pitot tube. A minimum of 5 points well distributed between about 0.05 and 5 inches of water should be obtained. By eye, sketch in a smooth curve and read the value of C_p for the point of ΔP_{avg} obtained in the field test. Use this C_p in subsequent calculations.

Also, if the two calibration curves (i.e., that of the auditor and that of the field team) differ by as much as 0.02 units on the C_p scale, the field team's standard pitot tube (or NBS-calibrated Type-S pitot tube) should be checked against the auditor's standard to determine if the difference was due to a difference in the standard pitot tubes or if it was due to poor calibration techniques. In all cases the auditor's NBS-calibrated standard pitot tube will be accepted as correct.

4.2.4 Calculate the Volumetric Flow Rate

Calculate the volumetric flow rate using the relationship discussed on page 22, namely;

$$Q_{sa} = 5.45 \times 10^6 \left(1 - B_{wo}\right) A\ C_p\ (\sqrt{\Delta P})_{avg} \left[\frac{P_s}{M_s \left(T_s\right)_{avg}}\right]^{1/2}$$

where Q_{sa} = audit value for the volumetric flow rate, dry basis, standard conditions of 530°R and 29.92 inches of Hg, ft^3/hr,

B_{wo} = the value for proportion by volume of water vapor in the gas stream,

A = value of the cross-sectional area of stack, ft^2,

C_p = audit value of the calibration coefficient of the Type-S pitot tube, dimensionless,

$(\sqrt{\Delta P})_{avg}$ = average of the square roots of the velocity heads as recorded by the auditor in the field, (inches of $H_2O)^{1/2}$,

P_s = absolute stack gas pressure calculated as the sum of the stack static pressure, P_g, and the value of barometric pressure, P_{bar}, inches of Hg,

M_s = value of the molecular weight of stack gas (wet basis), lb/lb-mole, and

$\left(T_s\right)_{avg}$ = value of average absolute stack gas temperature, °R.

4.2.5 Compare Audit and Field Test Results

Obtain the volumetric flow rate, Q_s, as calculated by the field team for the field test being audited. Compare the audit and field test values by

$$d_j = Q_{s_j} - Q_{sa_j}$$

where d_j = the difference in the audit and field test results for the j^{th} audit, ft^3/hr,

Q_{sa} = audit value of volumetric flow rate, ft^3/hr, and

Q_s = volumetric flow rate calculated by the field team, ft^3/hr.

Record the value of d_j in the quality audit log book.

4.2.6 Overall Evaluation of Field Team Performance

In a summary-type statement the field team should be evaluated on its overall performance. Reporting the d_j value as previously computed is an adequate representation of all the objective information collected for the audit. However, unmeasurable errors can result from non-adherence to the prescribed operating procedures and/or from poor technique in executing the procedures. These error sources have to be estimated subjectively by the auditor. Using the notes taken in the field, the team could be rated on a scale of 1 to 5 as follows:

5 - Excellent
4 - Above average
3 - Average
2 - Acceptable, but below average
1 - Unacceptable performance.

In conjunction with the numerical rating, the auditor should include justification for the rating. This could be in the form of a list of the team's strong/weak points.

The rating is reported to the manager. The field team should be notified of its rating, including the justification, through the manager.

4.3 DATA QUALITY ASSESSMENT

Two aspects of data quality assessment are considered in this section. The first considers a means of estimating the precision and accuracy of the reported data, e.g., reporting the bias, if any, and standard deviation associated with the measurements. The second consideration is that of testing the data quality against given standards using sampling by variables. For example, lower and upper limits, L and U, may be selected to include a large percentage of the measurements and outside of which it is desired to control the percentage of measurements to, say, less than 10 percent. If the data quality is not consistent with these limits, L and U, then action is taken to correct the possible deficiency before future field tests are performed and to correct the previous data when possible.

4.3.1 Estimating the Precision/Accuracy of the Reported Data

Methods for estimating the precision (standard deviation) and accuracy (bias) of the data are given in Section 4.1. In order to obtain these measures, it is required to estimate the standard deviations, means, and coefficients of variation of each of the variables listed in Tables 3 and 4. It is clear from examination of these tables that the largest potential sources of variation are the errors in calibrating the pitot tube, C_p, and in measuring the ΔP. These two contribute about 95 and 85 percent, respectively, of the standard deviation of the measured V_s and Q_s. In order to obtain an overall assessment of the data, the coefficients of variation can be taken directly from Tables 3 and 4, or obtained independently and substituted in these tables for the estimated values. In the following discussion, the procedures for estimating the standard deviation, mean, and coefficient of variation of the calibration coefficient, C_p, will be described.

Suppose that the value of C_p obtained through routine field data collection is denoted by C_{pf} and that obtained through the audit by C_{pa}. The difference is denoted by

$$d(C_p) = C_{pf} - C_{pa}$$

Let n stacks be audited out of N = 20 stacks and then denote the average difference by $\bar{d}(C_p)$ and the standard deviation of the difference by $s\{d(C_p)\}$. The $\bar{d}(C_p)$ measures the average bias in the measurements, and the relative bias can be obtained by dividing it by the average value of C_{pa}. The standard deviation $s\{d(C_p)\}$ is a measure of the precision of the data, and because $d(C_p)$ is the difference of two measurements each of which may be assumed to have the same precision, $\sigma\{d(C_p)\}$, should be equal to $\sqrt{2}\ \sigma\{C_p\}$, that is, $\sqrt{2}$ times the standard deviation associated with measurements of C_{pf} or C_{pa}. (See Final Report on this contract for further discussion on this point.) The coefficient of variation is then obtained by dividing $s\{C_p\}$ by the mean value of C_p, say $\bar{C}_{pa}$, then multiplying by 100 to express in percent. Table 6 contains an example calculation of CV starting with the differences.

In a similar manner, the relative bias and standard deviation of the $(\sqrt{\Delta P})_{avg}$ may be calculated, and these values inserted in the computations of Tables 3, 4, and 5 along with values for the other variables. The resulting biases and coefficients of variation of V_s and Q_s will be obtained.

The data can then be reported as the measured value, less the estimated bias, plus or minus the estimated CV, expressed in percent, times the mean value, i.e.,

$$X_M - \hat{\tau}_X \pm s\{X\}$$

or

$$X_M - \hat{\tau}_X \pm CV\{X\} \cdot \bar{X}$$

where X denotes the particular measurement of interest, in this case V_s or Q_s. If the bias is relative (i.e., expressed as a percent), then it must also be multiplied by the mean value $\bar{X}$. Inserting an appropriate multiple of s{X} in the above equation will result in an interval which should include a desired percentage of the measurements in the sampled population under the assumption that the measurements are normally distributed.

Because the sample sizes are small, it would be preferable to use the tolerance coefficient assuming normality. See Reference 13, pages 311-316, for a detailed description of this use of tolerance intervals. A table is given on page 315 of Reference 13. For example, if n = 5 and it is desired to include 90 percent of the sampled population of measurements with 90 percent confidence, then the coefficients would be taken to be 3.14. Note that this is considerably larger than the 1.64 which would be appropriate if the sample size were large.

4.3.2 Sampling by Variables

Because the lot size is small, N = 20, and consequently the sample size is small, say of the order n = 3 to 8, it is important to consider a sampling by variables approach to assess the data quality with respect to prescribed limits. That is, it is desired to make as much use of the data as possible. In the variables approach, the means and standard deviations of the sample of n audits are used in making a decision concerning the data quality.

Some background concerning the assumptions and the methodology is repeated below for convenience. However, one is referred to one of a number of publications having information on sampling by variables; e.g., see Refs. 11, 12, 13, 14, 15, and 16. The discussion below will be given in regard to the specific problem herein which has some unique features as compared with the usual variable sampling plans.

In the following discussion it is assumed that only C_p and ΔP are audited as directed in 4.2.2 and 4.2.3 and that these values are inserted in equations (1) and (2) along with the measured values of the remaining variables to obtain measured (field team's value) and audited values of V_s and Q_s.

Table 6. COMPUTATION OF MEAN DIFFERENCE, $\bar{d}$, AND STANDARD DEVIATION OF DIFFERENCES, s_d

General Formulas $d = Q_s - Q_{sa}$		Specific Example Data (ft^3/hr)
d_1	d_1^2	-1.7×10^4
d_2	d_2^2	-2.5×10^4
d_3	d_3^2	-1.1×10^4
d_4	d_4^2	-3.9×10^4
d_5	d_5^2	-0.9×10^4
d_6	d_6^2	1.2×10^4
d_7	d_7^2	2.9×10^4
Σd_j	$\Sigma d_j^{\,2}$	-4.2×10^4, 36.22×10^8

$$\bar{d} = \frac{\Sigma d_j}{n} \qquad \bar{d} = -0.6 \times 10^4 \ ft^3/hr$$

$$s_d^{\,2} = \frac{\Sigma d_j^{\,2} - \frac{(\Sigma d_j)^2}{n}}{(n-1)} \qquad s_d^{\,2} = 5.62 \times 10^8$$

$$s_d = \sqrt{s_d^{\,2}} \qquad s_d = 2.37 \times 10^4 \ ft^3/hr$$

Table 7. SAMPLE PLAN CONSTANTS, k for P{not detecting a lot with proportion outside limits L and U = p} ≤ 0.1

Sample Size n	p = 0.2	p = 0.1
3	3.039	4.258
5	1.976	2.742
7	1.721	2.334
10	1.595	2.112
12	1.550	2.045

The value of the volumetric flow rate obtained in a routine manner by the field team is denoted by Q_s, measured value. Let the audited value be denoted by Q_{sa}. The difference between these values will be designated as d_j, and the mean difference over n audits by $\bar{d}$. That is,

$$\bar{d} = \frac{\sum_{j=1}^{n} \left(Q_{s_j} - Q_{sa_j} \right)}{n} .$$

Theoretically, Q_s and Q_{sa} should be measures of the same volumetric flow rate, and their difference should have a mean of zero on the average. In addition, this difference should have a standard deviation equal to $\sqrt{2}$ times that associated with measurements of Q_s or Q_{sa}. Recall from the variance analysis that the coefficient of variation of Q_s, $CV\{Q_s\}$, was estimated to be about 1.97 percent based on only the two most important variables or the estimated standard deviation; i.e., $\hat{\sigma}\{Q_s\} \simeq 0.020$ (mean value of Q_s). For a mean value $\mu\{Q_s\} = 199 \times 10^4$ ft^3/hr, $\hat{\sigma}\{Q_s\} \simeq 4.0 \times 10^4$ ft^3/hr. A difference of two such measurements would have a standard deviation approximately equal to

$$4.0\sqrt{2} \times 10^4 \ ft^3/hr.$$

Assuming three σ limits, the values $-3(4.0\sqrt{2}) \times 10^4$ and $3(4.0\sqrt{2}) \times 10^4 ft^3/hr$ define lower and upper limits, L and U, respectively, outside of which it is desired to control the proportion of differences, d_j. Following the method given in Ref. 14, a procedure for applying the variables sampling plan is described below. Figures 8 and 9 illustrate examples of satisfactory and unsatisfactory data quality with respect to the prescribed limits L and U.

The variables sampling plan requires the sample mean difference, $\bar{d}$; the standard deviation of these differences, s_d; and a constant, k, which is determined by the value of p, the proportion of the differences outside the limits of L and U. For example, if it is desired to control at 0.10 the probability of not detecting lots with data quality p equal to 0.20 (or 20% of the measurements outside L and U) and if the sample size n = 7, then the value of k can be obtained from Table II of Ref. 14. The values of $\bar{d}$ and s_d are computed in the usual manner; see Table 6 for formulas and

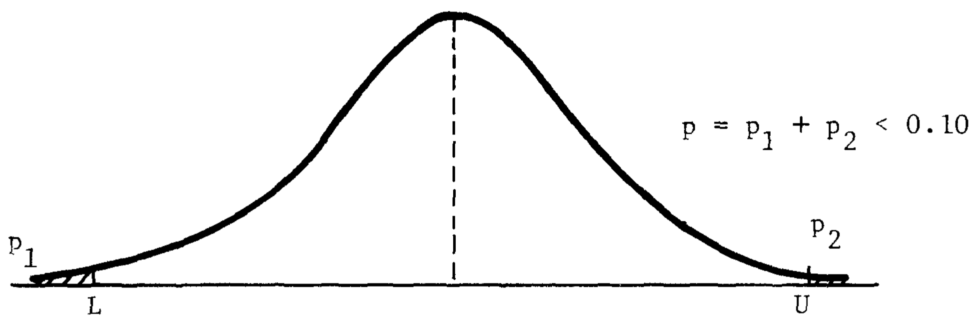


Figure 8. Example Illustrating $p < 0.10$ and Satisfactory Data Quality.

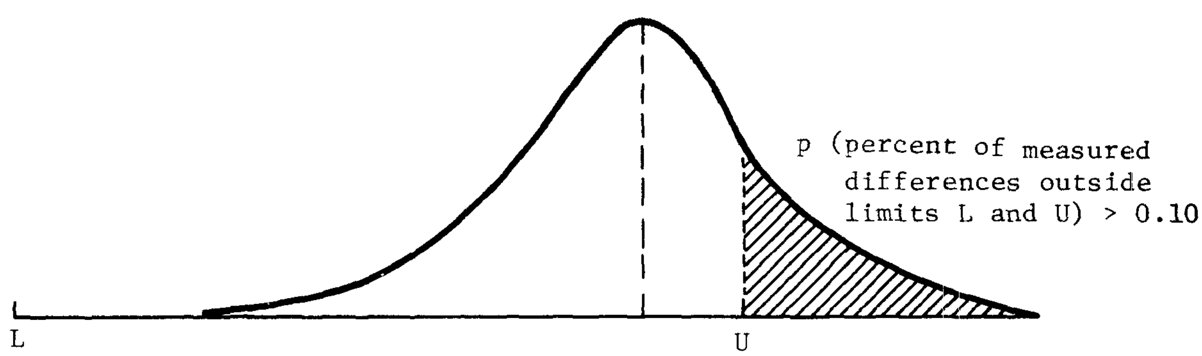


Figure 9. Example Illustrating $p > 0.10$ and Unsatisfactory Data Quality.

a specific example. Given the above information, the test procedure is applied and subsequent action is taken in accordance with the following criteria:

(1) If <u>both</u> of the following conditions are satisfied:

$$\bar{d} - k\, s_d \geq L = -\, 12\sqrt{2} \times 10^4 \text{ ft}^3/\text{hr},$$

$$\bar{d} + k\, s_d \leq U = 12\sqrt{2} \times 10^4 \text{ ft}^3/\text{hr},$$

the measurements are considered to be consistent with the prescribed data quality limits and no corrective action is required.

(2) If one or both of these inequalities is violated, possible deficiencies exist in the measurement process as carried out for that particular lot (group) of field tests. These deficiencies should be identified and corrected before future field tests are performed. Data corrections should be made when possible.

Table 7 contains a few selected values of n, p, and k for convenient reference.

Using the values of $\bar{d}$ and s_d in Table 6, k = 1.721 for a sample size n = 7, and p = 0.20, the test criteria can be checked; i.e.,

$$\bar{d} - 1.721\, s_d = -\, 4.68 \times 10^4 \text{ ft}^3/\text{hr} > L,$$

$$\bar{d} + 1.721\, s_d = 3.48 \times 10^4 \text{ ft}^3/\text{hr} < U.$$

Therefore, both conditions are satisfied and the lot of N = 20 measurements is consistent with the prescribed quality limits. The plan protects one from not detecting lots with 20 percent or more defects (deviations falling outside the designated limits L and U) with a risk of 0.10.

METHOD 2—DETERMINATION OF STACK GAS VELOCITY AND VOLUMETRIC FLOW RATE (TYPE S PITOT TUBE)

1. *Principle and applicability.*

1 1 Principle. Stack gas velocity is determined from the gas density and from measurement of the velocity head using a Type S (Stauscheibe or reverse type) pitot tube

1 2 Applicability. This method should be applied only when specified by the test procedures for determining compliance with the New Source Performance Standards.

2. *Apparatus.*

2 1 Pitot tube—Type S (Figure 2-1), or equivalent, with a coefficient within ±5% over the working range.

2 2 Differential pressure gauge—Inclined manometer, or equivalent, to measure velocity head to within 10% of the minimum value.

2 3 Temperature gauge—Thermocouple or equivalent attached to the pitot tube to measure stack temperature to within 1.5% of the minimum absolute stack temperature

2 4 Pressure gauge—Mercury-filled U-tube manometer, or equivalent, to measure stack pressure to within 0 1 in Hg.

2 5 Barometer—To measure atmospheric pressure to within 0 1 in. Hg.

2 6 Gas analyzer—To analyze gas composition for determining molecular weight.

2 7 Pitot tube—Standard type, to calibrate Type S pitot tube.

3 *Procedure.*

3 1 Set up the apparatus as shown in Figure 2-1 Make sure all connections are tight and leak free. Measure the velocity head and temperature at the traverse points specified by Method 1.

3 2 *Measure the static pressure in the stack.*

3 3 Determine the stack gas molecular weight by gas analysis and appropriate calculations as indicated in Method 3.

4. *Calibration*

4 1 To calibrate the pitot tube, measure the velocity head at some point in a flowing gas stream with both a Type S pitot tube and a standard type pitot tube with known coefficient. Calibration should be done in the laboratory and the velocity of the flowing gas stream should be varied over the normal working range. It is recommended that the calibration be repeated after use at each field site.

4 2 Calculate the pitot tube coefficient using equation 2-1.

$$C_{p_{test}} = C_{p_{std}} \sqrt{\frac{\Delta p_{std}}{\Delta p_{test}}} \quad \text{equation 2-1}$$

where:

$C_{p_{test}}$ = Pitot tube coefficient of Type S pitot tube.

$C_{p_{std}}$ = Pitot tube coefficient of standard type pitot tube (if unknown, use 0 99).

Δp_{std} = Velocity head measured by standard type pitot tube.

Δp_{test} = Velocity head measured by Type S pitot tube.

4 3 Compare the coefficients of the Type S pitot tube determined first with one leg and then the other pointed downstream. Use the pitot tube only if the two coefficients differ by no more than 0 01.

5. *Calculations.*

Use equation 2-2 to calculate the stack gas velocity.

$$(V_s)_{avg.} = K_p C_p (\sqrt{\Delta p})_{avg.} \sqrt{\frac{(T_s)_{avg.}}{P_s M_s}}$$

Equation 2-2

where

$(V_s)_{avg}$ = *Stack gas velocity, feet per second (f p.s.).*

$K_p = 85.48 \frac{ft}{sec.} \left(\frac{lb}{lb. mole \, ^\circ R}\right)^{1/2}$ when these units are used.

C_p = Pitot tube coefficient, dimensionless.

$(T_s)_{avg}$ = Average absolute stack gas temperature, °R.

$(\sqrt{\Delta p})_{avg}$ = Average velocity head of stack gas, inches H_2O (see Fig. 2-2).

P_s = Absolute stack gas pressure, inches Hg

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

$M_d(1-B_{wo})+18B_{wo}$

M_d = Dry molecular weight of stack gas (from Method 3)

B_{wo} = Proportion by volume of water vapor in the gas stream (from Method 4).

Figure 2-2 shows a sample recording sheet for velocity traverse data. Use the averages in the last two columns of Figure 2-2 to determine the average stack gas velocity from Equation 2-2.

Use Equation 2-3 to calculate the stack gas volumetric flow rate.

$$Q_s = 3600 \, (1 - B_{wo}) V_s A \left(\frac{T_{std}}{(T_s)_{avg}}\right) \left(\frac{P_s}{P_{std}}\right)$$

Equation 2-3

where

Q_s = Volumetric flow rate, dry basis, standard conditions, $ft.^3/hr$

A = *Cross-sectional area of stack,* ft^2

T_{std} = Absolute temperature at standard conditions, 530° R.

P_{std} = Absolute pressure at standard conditions, 29.92 inches Hg.

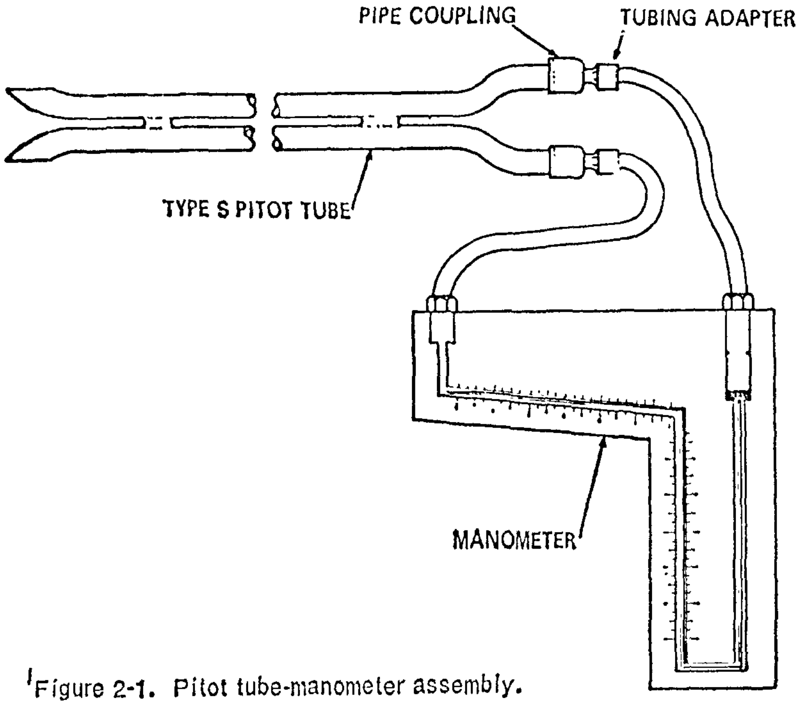


Figure 2-1. Pitot tube-manometer assembly.

6. *References.*

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PLANT____________________

DATE____________________

RUN NO.____________________

STACK DIAMETER, in.____________________

BAROMETRIC PRESSURE, in. Hg.____________________

STATIC PRESSURE IN STACK (P_g), in. Hg.__________

OPERATORS____________________

SCHEMATIC OF STACK CROSS SECTION

Traverse point number	Velocity head, in. H_2O	$\sqrt{\Delta p}$	Stack Temperature (T_S), °F
	AVERAGE:		

Figure 2-2. Velocity traverse data.

APPENDIX B GLOSSARY OF SYMBOLS

This is a glossary of symbols as used in this document. Symbols used and defined in the reference method (Appendix A) are not repeated here.

SYMBOL	DEFINITION
N	Lot size
n	Sample size for the quality audit (Section IV)
CV{X}	Assumed or known coefficient of variation ($100\ \sigma_X/\mu_X$) of a population
$\widehat{CV}\{X\}$	Computed coefficient of variation ($100\ s_X/\bar{X}$) from a finite sample of measurements
σ_X	Assumed standard deviation of the parameter X (population standard deviation).
s_X	Computed standard deviation of a finite sample of measurements (sample standard deviation)
μ_X	Assumed mean value of the parameter X (population mean)
$\bar{X}$	Computed average of a finite sample of measurements (sample mean)
$\hat{\tau}_X$	Computed bias of the parameter X for a finite sample (sample bias).
ε_X	Random error associated with the measurement of parameter X
d_j	The difference in the audit value and the value arrived at by the field crew for the j^{th} audit
$\bar{d}$	Mean difference between Q_s and Q_{sa} for n audits
s_d	Estimated standard deviation of difference between Q_s and Q_{sa}
p	Percent of measurements outside specified limits L and U
k	Constant used in sampling by variables (Section IV)

SYMBOL	DEFINITION
L	Lower quality limit used in sampling by variables
U	Upper quality limit used in sampling by variables
CL	Center line of a quality control chart
LCL	Lower control limit of a quality control chart
UCL	Upper control limit of a quality control chart
A	Inside cross-sectional area of stack
d	Inside diameter of a circular stack
C	Circumference of stack
t	Stack wall thickness
D_c	Percent difference in a new calibration checkpoint and the current calibration curve for a given ΔP
D_T	Percent difference in the absolute ambient temperature expressed in °R as measured by the regular temperature measuring system and a mercury bulb thermometer
D_b	Percent difference in barometric pressure (inches of mercury) as measured by the field barometer and a mercury barometer
Q_{sm}	Volumetric flow rate as measured by the field team
Q_{sa}	Volumetric flow rate as determined by the auditor
$\bar{Q}_s$	The average volumetric flow rate resulting from several replications by the field team under fixed process conditions
C_{pf}	Type-S pitot tube coefficient as determined from the field team's calibration
C_{pa}	Type-S pitot tube coefficient as determined from the auditor's calibration check
$C_{p_{max}}$	Maximum value of the Type-S pitot tube coefficient over a specified ΔP range
$C_{p_{min}}$	Minimum value of the Type-S pitot tube coefficient over a specified ΔP range
$C_{p_{avg}}$	Average value of the Type-S pitot tube coefficient over a specified ΔP range

APPENDIX C GLOSSARY OF TERMS

The following glossary lists and defines the statistical terms as used in this document.

Accuracy . . . . . . A measure of the error of a process expressed as a comparison between the measured value and the true value.

Bias . . . . The systematic or non-random component of system error.

Lot. . . . . A specified number of objects to be treated as a group.

Measurement Method . A set of procedures for making a measurement.

Measurement Process. The process of making a measurement including method, personnel, equipment, and environmental conditions.

Population . . . . . A very large number of like objects (i.e., measurements, checks, etc.) from which the true mean and standard deviation can be deduced with a high degree of accuracy.

Precision. . . . . . The degree of variation among measurements on a homogeneous material under controlled conditions, and usually expressed as a standard deviation or, as is done here, as a coefficient of variation.

Quality Audit. . . . A management tool for independently assessing data quality.

Quality Control Check . . . . . . Checks made by the field crew on certain items of equipment and procedures to assure data of good quality.

Sample . . . . Objects drawn usually at random from the lot for checking.

APPENDIX D CONVERSION FACTORS

Conversion factors for converting the U.S. customary units to the International System of Units (SI) are given below (Ref. 16).

To Convert From	To	Multiply By
	Length	
foot	meter (m)	0.3048
inch	meter (m)	0.0254
	Pressure	
inch of mercury (in Hg) (32°F)	Newton/meter^2 (N/m^2)	3386.389
inch of mercury (in Hg) (60°F)	Newton/meter^2 (N/m^2)	3376.85
millimeter mercury (mmHg) (32°F)	Newton/meter^2 (N/m^2)	133.3224
inch of water (in H_2O) (29.2°F)	Newton/meter^2 (N/m^2)	249.082
inch of water (in H_2O) (60°F)	Newton/meter^2 (N/m^2)	248.84
	Force	
pound-force (lbf avoirdupois)	Newton (N)	4.448222
	Mass	
pound-mass (lbm avoirdupois)	kilogram (kg)	0.4535924
	Temperature	
degree celsius	kelvin (K)	$t_K = t_c + 273.15$
degree Fahrenheit	kelvin (K)	$t_K = (t_F+459.67)/1.8$
degree Rankine	kelvin (K)	$t_K = t_R/1.8$
degree Fahrenheit	degree celsius	$t_C = (t_F - 32)/1.8$
kelvin	degree celsius	$t_C = t_K - 273.15$
	Velocity	
foot/second	meter/second (m/s)	0.3048
foot/minute	meter/second (m/s)	0.00508
	Volume	
cubic foot (ft^3)	meter^3 (m^3)	0.02832
	Volume/Time	
foot^3/minute	meter^3/second (m^3/s)	0.0004719
foot^3/second	meter^3/second (m^3/s)	0.02832

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16. ABSTRACT

Guidelines for the quality assurance of average stack gas velocity and volumetric flow rate measurements by the Federal reference method are presented. These inclued:

1. Good operating practices.
2. Directions on how to assess performance and qualify data.
3. Directions on how to identify trouble and improve data quality.
4. Directions to permit design of auditing activities.

The document is not a research report. It is designed for use by operating personnel.

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Quality Control		14D
Air Pollution		13B
Velocity		14G
Pitot Tube		14B

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