AN AMERICAN NATIONAL STANDARD

ASME
PTC 21-1991
(REVISION OF
PTC 21-1941)

Particulate Matter Collection Equipment

PERFORMANCE
TEST
CODES

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center
345 East 47th Street New York, N.Y. 10017

Particulate Matter Collection Equipment

PERFORMANCE TEST CODES

ASME PTC 21-1991
(REVISION OF PTC 21-1941)

AN AMERICAN NATIONAL STANDARD

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N.Y. 10017

Date of Issuance: December 23, 1991

This document will be revised when the Society approves the issuance of the next edition, scheduled for 1996. There will be no Addenda issued to PTC 21-1991.

Please Note: ASME issues written replies to inquiries concerning interpretation of technical aspects of this document. PTC 21-1991 is being issued with an automatic subscription service to the interpretations that will be issued to it up to the publication of the 1996 edition.

FOREWORD

(This Foreword is not part of ASME PTC 21-1991.)

The need to update the 1941 version of this Code (PTC 21-1941, Dust Separating Apparatus) led to the reorganization of the PTC 21 Committee in 1980. In the course of the complete revision, the scope was broadened beyond that of the original document, leading to the current more comprehensive title and content. The PTC 21 code draft was approved by the Board on Performance Test Codes on June 1, 1990. The Code was adopted by the American National Standards Institute as an American National Standard on August 16, 1991.

PERSONNEL OF PERFORMANCE TEST CODE COMMITTEE NO. 21 ON PARTICULATE MATTER COLLECTION EQUIPMENT

(The following is the roster of the Committee at the time of approval of this Code.)

OFFICERS

A. L. Plumley, *Chairman*
E. Bakke, *Vice Chairman*
G. Osolsobe, *Secretary*

COMMITTEE PERSONNEL

E. Bakke, Peabody Process Systems Inc.
W. A. Crandall, Consultant
Y. Goland, Rockwell International Inc.
R. P. Perkins, E. I. DuPont de Nemours & Co.
A. A. Petersen, Consultant
A. L. Plumley, Combustion Engineering Inc.

(The Committee wishes to acknowledge the contribution of past member Lee Coe.)

BOARD ON PERFORMANCE TEST CODES

CONTENTS

SECTION 0 — INTRODUCTION

0.1 The term *particulate matter collection equipment* is intended to include all devices used for separating gas borne particles from the medium in which they are transported. This Code is designed to cover efficiency determination and performance testing for all types of particulate matter collection equipment installed in conjunction with both industrial and utility combustion processes. Its use for other gas streams is not precluded if test parameters are compatible with those discussed in PTC 38, Determining the Concentration of Particulate Matter in a Gas Stream.

Particulate matter collection equipment includes, but is not limited to, the following devices or combinations thereof: baghouse, fabric filter, mechanical collector, catcher, cyclone, eliminator, filter, wet or dry electrostatic precipitator, wet or dry scrubber, trap, washer, and fixed or moving bed filter.

0.2 Unless otherwise specified, all references to other test codes are to ASME Performance Test Codes, latest edition.

0.3 This Code provides recommended test procedures and instrumentation for determination of efficiency and performance of particulate matter collection equipment used to control emissions from combustion processes. It is the intent of this Code to minimize uncertainty so that final efficiency results do not exceed $\pm 2\%$. Uncertainty, however, depends upon actual values measured and utilized in a given test.

0.4 Test objective(s) shall be agreed to by the interested parties prior to the test.

0.5 The following ASME documents should be available to the user of this Code: PTC 28, Determining the Properties of Fine Particulate Matter; PTC 38, Determining the Concentration of Particulate Matter in a Gas Stream; and PTC 19.1, Measurement Uncertainty.

0.6 Unless otherwise indicated, the technical terms and numerical constants which are used in this Code have the meanings and values as defined in Section 2.

0.7 Test results shall be reported as determined, and only tests which comply with the requirements of this Code may be designated as "ASME PTC 21 Code Approved."

SECTION 1 — OBJECT AND SCOPE

1.1 The object of the test is to determine the performance characteristics of equipment designed to collect particulate matter from a gas stream. This Code specifies methods for determining the performance of the equipment with regard to the following:

(a) overall mass collection efficiency of the equipment;

(b) particulate matter concentration at inlet and outlet of collector;

(c) efficiency of collection according to size of particle;

(d) resistance to gas flow, i.e., the total pressure drop across the equipment;

(e) quantity of gas passing through the equipment; and

(f) power consumption of the collection equipment.

1.2 The rules and instructions included in this Code are for the particulate matter collection equipment proper, as indicated by para. 1.1. If the scope of the test includes any auxiliary apparatus, it will be necessary to consult other ASME codes, as applicable.

1.3 The determination of the particulate matter count, extensively used as a measure of atmospheric particulate matter pollution, is outside the scope of this Code.

1.4 This Code cautions against the extrapolation of the performance of a complete particulate matter collection installation on the basis of testing only a single unit of multiple unit equipment.

1.5 Should specific directions given in this Code for any particular measurement differ from those given in other ASME Performance Test Codes for similar measurements, the instructions of this Code shall prevail, unless otherwise agreed by the parties to the test.

1.6 This Code specifies the desired conditions and procedures for obtaining valid and accurate test results. Factors affecting overall test accuracy and validity are considered in paras. 5.4 and 5.5.

SECTION 2 — DEFINITIONS AND DESCRIPTIONS OF TERMS

2.1 This Code specifies the procedures to be employed in determining the efficiency of particulate matter collection equipment. The terms used in connection with the procedures are defined in PTC 38. Table 1 is an alphabetized and updated version of Table 2.1 in PTC 38-1980.

2.2 For the purpose of this Code, *particulate matter* is defined as finely divided material, other than uncombined water, suspended in a gas stream at the prevailing temperature of the gas stream under consideration — such material being separable from the gas phase by filtration when using the agreed upon sampling apparatus and procedures described in this Code.

This definition is intended to exclude from consideration those substances which may be formed:

(*a*) outside the stack or duct;

(*b*) in a sampling train; or

(*c*) upon cooling the gas stream to a lower temperature than at the inlet.

2.3 The definitions of specific terms with subscripts utilized in this Code are described in the appropriate parts of the text.

TABLE 1 LISTING OF SYMBOLS, UNITS OF MEASURE, AND CONVERSION FACTORS

Term	Symbol	Description	U.S. Conventional Units		Multiply by These Conversion Factors to Obtain SI Units		SI Units	
			Units	Name of Unit			Units	Name of Unit
Area	A	Cross-sectional area	in.^{2}	square inches	6.452	E−04	m^2	square meters
			ft^2	square feet	9.290	E−02	m^2	square meters
			cm^2	square centimeters	1.000	E−04	m^2	square meters
Concentration	C	Weight of material in volume of gas or liquid	lbm/ft^3	pounds per cubic foot	1.602	E+01	kg/m^3	kilograms per cubic meter
			lbm/gal	pounds per gallon	1.198	E+02	kg/m^3	kilograms per cubic meter
			mg/m^3	milligrams per cubic meter	1.000	E−06	kg/m^3	kilograms per cubic meter
Density	ρ	Density of material	lbm/ft^3	pounds per cubic foot	1.602	E+01	kg/m^3	kilograms per cubic meter
			lbm/gal	pounds per gallon	1.198	E+02	kg/m^3	kilograms per cubic meter
			g/cm^3	grams per cubic centimeter	1.000	E−03	kg/m^3	kilograms per cubic meter
Efficiency	E	Overall mass fractional collection efficiency	%	percent	1.000	E+00	%	percent
Electrical power	W	Electrical power	W	watt	1.000	E+00	W or J/s	Watts or Joules per second
Energy, electrical	KWH	Electrical energy	kW·h	kilowatt hour	3.600	E+06	J or N·m	Joule or Newton meter
Energy, thermal	HV	Heating value of fuel	Btu	British Thermal Unit	1.055	E+03	J or N·m	Joule or Newton meter
			Cal	calorie	4.186	E+00	J or N·m	Joule or Newton meter
Flow rate, mass	G	Mass flow rate	lbm/hr	pounds per hour	1.260	E−04	kg/s	kilograms per second
			lbm/min	pounds per minute	7.560	E−03	kg/s	kilograms per second
Flow rate, volumetric	Q	Volumetric flow rate	CFM	cubic feet per minute	4.720	E−04	m^3/s	cubic meters per second
			GPM	gallons per minute	6.308	E−05	m^3/s	cubic meters per second
Force	F	Force	lbf	pound force	4.448	E+00	N	Newton, kg·m/s^2
			pdl	poundal	1.383	E−01	N	Newton, kg·m/s^2
			kgf	kilogram force	9.807	E+00	N	Newton, kg·m/s^2
			dyne	dyne	1.000	E−02	N	Newton, kg·m/s^2
Gravitational Constant	g	Gravitational constant	ft/sec^2	32.17 ft/sec^2	3.048	E−01	m/s^2	9.807 m/s^2
			cm/sec^2	980 cm/sec^2	1.0	E−02	m/s^2	9.807 m/s^2
Length	L	Dimension or distance	in.	inch	2.540	E−02	m	meter
			ft	foot	3.048	E−01	m	meter
			mm	millimeter	1.000	E−03	m	meter
			cm	centimeter	1.000	E−02	m	meter

TABLE 1 LISTING OF SYMBOLS, UNITS OF MEASURE, AND CONVERSION FACTORS (CONT'D)

Term	Symbol	Description	U.S. Conventional Units		Multiply by These Conversion Factors to Obtain SI Units	SI Units	
			Units	Name of Unit		Units	Name of Unit
Mass	Wt	Weight of material	lbm	pound mass (avoir)	4.536 E−01	kg	kilogram
			ton	ton	9.072 E+02	kg	kilogram
			gr	grain (avoir)	6.480 E−05	kg	kilogram
			g	gram	1.000 E−03	kg	kilogram
Particle size	*D*	Diameter of particle	μm	micron or micrometer	1.000 E−06	m	meter
Particle, weight percentage	*S*	Percentage by weight of particles of given diameter larger or smaller than	%	percent	1.000 E+00	%	percent
Pressure	*P*	Pressure, gas or liquid	lbf/in.^{2}	pounds per square inch	6.895 E+03	Pa	Pascals, N/m^2
			in. H_2O	inches water gage	2.491 E+02	Pa	Pascals, N/m^2
			in. Hg	inches Hg manometer	3.387 E+03	Pa	Pascals, N/m^2
			mm Hg	millimeters Hg manometer	1.333 E+02	Pa	Pascals, N/m^2
			Atm	atmospheres	1.014 E+05	Pa	Pascals, N/m^2
			bar	bars	1.000 E+05	Pa	Pascals, N/m^2
Temperature	*T*	Temperature, object or material	°F	degrees Fahrenheit	°F−32/1.8	°C	degrees Celsius
			°R	degrees Rankine	°R/1.8	°C	degrees Celsius
			°C	degrees Centigrade	1.000	°C	degrees Celsius
			°K	degrees Kelvin	°K−273.15	°C	degrees Celsius
Temperature differential	ΔT	Temperature drop	°F	degrees Fahrenheit	5.556 E−01	°C	degrees Celsius
			°C	degrees Centigrade	1.000 E−00	°C	degrees Celsius
Time	*t*	Duration of time	sec	second	1.000 E+00	s	second
			min	minute	6.000 E+01	s	second
			hr	hour	3.6 E+03	s	second
Velocity	*V*	Velocity, object or material	ft/sec	feet per second	3.048 E−01	m/s	meters per second
			in./sec	inches per second	2.540 E−02	m/s	meters per second
			cm/sec	centimeters per second	1.000 E−02	m/s	meters per second
Viscosity	η	Viscosity, gas or liquid	poise	poise	1.000 E+00	P	poise (0.1 Pa·s)
Volume	Vol	Volume, space or material	ft^3	cubic feet	2.832 E−02	m^3	cubic meters
			gal	gallons (U.S.)	3.785 E−03	m^3	cubic meters
			l	liter	1.000 E−03	m^3	cubic meters
			ml	milliliter	1.000 E−06	m^3	cubic meters

GENERAL NOTE: Additional common conversion factors are contained in Appendix K of PTC 38-1980.

SECTION 3 — GUIDING PRINCIPLES

3.1 GENERAL

3.1.1 Determination of the performance of particulate matter collection equipment requires the use of measurements made in accordance with other test codes, especially PTC 28 (Determining the Properties of Fine Particulate Matter) and PTC 38 (Determining the Concentration of Particulate Matter in a Gas Stream). The procedures specified in such references provide numerous options for adapting the chosen techniques to suit the conditions under which measurements are to be made. It is incumbent upon the parties to a particular investigation to develop sufficient knowledge of the applicable conditions and options to ensure selection of correct procedures.

3.2 ITEMS OF AGREEMENT

3.2.1 Where the purpose of a test involves the interests of two or more parties, an agreement among these parties must be formulated in advance of the test.

The following is a checklist of pertinent items upon which agreement in writing should be reached by the parties to the test:

(a) objective(s) of the test;

(b) date and time of the test;

(c) number, type, and location of sample trains and other instruments where alternates are permitted and the test procedures to be employed in their use;

(d) number and location of all sampling and measurement points;

(e) operating conditions of the process, including type and rate of fuel fired;

(f) method of determining and maintaining constancy of process conditions during the test;

(g) gas flow rates in duct(s) or stack(s) to be tested;

(h) method of determining total gas flow; whether by combustion calculations, by process calculations, or by velocity head measurements;

(i) number and duration of runs;

(j) duration of steady state operation before sampling is commenced and, in the case of new or modified installations, the minimal "shakedown" operational period required prior to testing;

(k) designation of the procedures for making calibrations, weighings, and other appropriate measurements, and selection of the laboratories for carrying out various test procedures;

(l) maximum deviations of test measurements and conditions between duplicate runs that will be acceptable, and the requirements for additional runs where such deviations are exceeded;

(m) method for determination of collection efficiency (see para 3.5);

(n) format and content of report of results;

(o) portions of the tested equipment (if any) to be out of service during the test.

3.3 MEASUREMENT UNCERTAINTY

Ideal test conditions may be unobtainable in many test situations. This Code specifies the desired conditions and procedures for obtaining valid and accurate test results and also provides guidance for dealing with nonideal conditions. Factors affecting overall test accuracy are considered in Section 5. The concepts described, and the formulas shown, combined with information provided in PTC 19.1, are sufficient to perform a complete error analysis.

In conducting the efficiency test described in this Code, it is necessary to follow the directions of PTC 28 and PTC 38 in the selection of test equipment and instrumentation. The largest error is in the pitot measurement of total gas flow due to the possibilities of varying flow quantities during the test and flows not running exactly parallel to the duct-work. The error is usually on the side of higher than actual flow rate.

An example of the effects of variations in instrumentation and flow rates on the efficiencies of high performance equipment is shown in the following table:

	Effect on Efficiency, %, When	
Item Varied	Inlet Conditions Vary, Outlet Conditions Are Constant	Inlet Conditions Are Constant, Outlet Conditions Vary
Stack velocity head, +0.01 in. H_2O	0.011%	−0.009%
Orifice reading, +0.20 in. H_2O	0.000%	0.000%
Stack temperature, +10°F	−0.003%	0.003%
Sampler catch weight, +10%	0.050%	−0.055%
Oxygen in flue gas, +0.5%	−0.000%	0.000%
Stack gas flow rate, +11.76%	0.058%	−0.065%
Square root of the sum of the squares	±0.078%	±0.086%

The highest uncertainty would occur when the inlet and outlet gas flow rates varied in opposite directions, as shown below:

Stack gas inlet	−11.76%	−0.147%
Stack gas outlet	+11.76%	

Square root of the sum of the squares: ±0.158%

Details of the specific example are shown in Appendix F.

Provisions for less-than-desirable test conditions must be agreed upon in advance by all parties to the test. This agreement should be clearly stated in the test report.

3.4 WITNESS TO A TEST

3.4.1 Accredited representatives of all parties concerned should be present to witness that all aspects of the test are conducted in accordance with the agreements.

3.4.2 Should an accredited representative establish to all parties that the observed test procedures and conditions will invalidate or prejudice the test objectives, that portion of the test results, or the test run itself, shall be deleted.

3.5 METHODS OF TESTING

3.5.1 It is recommended that collection efficiency be calculated by simultaneous determinations of the mass of particulate matter entering and leaving the collection equipment.

3.5.2 In cases where reasonably accurate measurement of particulate matter at the inlet is excessively difficult or impossible, determination of collection efficiency by simultaneous measurement of the particulate matter collected by the equipment and that leaving the outlet may be considered by the parties to the test. It should be noted that accurate determination of the collector catch in a given test period may be difficult. If this measurement is to be used, the parties must carefully consider and agree upon procedures and equipment to be used, especially taking into account the tendency for varying residual deposits to be retained in the collector at the time of measurements.

3.5.3 Inlet and outlet particulate matter concentration in the gas stream shall be measured in accordance with the procedures, options, and precautions described in PTC 38.

3.5.4 When required, particle size distribution of particulate matter in the inlet and outlet gas streams shall be determined by the methods of PTC 28 (see para. 4.2.1).

3.5.5 Fractional mass efficiency by particle size can be determined for most particulate matter collection equipment only by simultaneous in-situ size measurement of the particulate matter in the inlet and outlet gas streams. Due to cohesive forces between particles, redispersion of fine particles captured in the collector (for the purpose of determination of particle size distribution) may not be possible with sufficient completeness to allow accurate calculation of fractional efficiency.

3.5.6 Calculation of collection efficiency may be done in accordance with the procedures appearing in Section 5.

SECTION 4 — INSTRUMENTS AND METHODS OF MEASUREMENT

4.1 INSTRUMENTS

4.1.1 Necessary Testing Apparatus. A list of required instruments is given in this Section. A detailed description of these instruments is given in PTC 38, Determining the Concentration of Particulate Matter in a Gas Stream. Before proceeding to select or construct instruments, those chapters of the PTC 19 series of Instruments and Apparatus Supplements dealing with these instruments should be consulted for detailed information.

(a) Standard pitot tubes or other calibrated devices for making gas velocity measurements in the gas stream.

(b) Sampling equipment — consisting of nozzles, sampling probes, and particulate matter collectors — for proper sampling of the gas stream and for collecting representative samples of the particulate matter entrained therein.

(c) Metering devices, usually orifices and/or gas meters, for determining the flue gas sampling rate and total volume.

(d) Exhausting devices for withdrawing the required gas samples.

(e) Thermometers or thermocouples with temperature indicator(s) for measuring the gas temperatures at the sampling locations in the gas stream, at the orifices or gas meters, and at the inlet and outlet of the collector.

(f) Inclined manometers, or instruments of equal or greater accuracy, for use with pitot tubes or other calibrated devices in reading gas velocity and/or velocity pressures.

(g) Inclined or vertical manometers, or gages of equal accuracy, for indicating the pressure drop across the metering orifices.

(h) Manometers or suitable gages for measuring the static pressure at the discharge of the metering orifice.

(i) Manometers or suitable gages for measuring the static pressure at the sampling location.

(j) Inclined or vertical manometers, or gages of equal accuracy, for determining pressure drop across the particulate collection device.

(k) A drying oven suitable for removing moisture from the samples and filters before weighing, and a desiccator, with fresh desiccant, to hold the samples and filters while cooling after drying and before weighing. Drying temperature shall be 105°C, or higher, to meet the requirements of specific sampling conditions.

(l) Orsat equipment, or other instrumentation of equal or better accuracy, for use in determining the analysis of the sampled gas. Such an analysis is required to permit correction to design excess air or percent O_2 basis and is necessary if gas flow rates are to be determined by combustion calculations or other stoichiometric means. The Orsat apparatus and its operation are described in PTC 19.10, Flue and Exhaust Gas Analyses. Fuel samples, rates, and analyses are required for combustion calculations.

(m) Timing device.

(n) Barometer.

(o) Humidity measurement equipment.

(p) Equipment for measuring particle size distribution of the particles in the inlet and outlet ducts.

(q) Voltmeter, ammeter, and wattmeter to measure electrical energy consumption.

(r) Weighing equipment for determining the amount of particulate matter caught, when the particulate matter is caught dry and when the weighing equipment does not interfere with the operation of the particulate matter collection equipment.

4.2 DESCRIPTION OF INSTRUMENTS

Detailed descriptions of instruments not covered by PTC 38 are given below.

4.2.1 Particle Size Analysis Equipment. Detailed description of particle size analysis equipment is beyond the scope of this Code (see PTC 28 and Section 7, references 2 and 3).

The particle size distribution measurement is done preferably with in-situ instruments such as cascade impactors during the testing period (see para. 3.5.5).

Experience indicates that no single method for size analysis of particulate matter will give reliable results for all types of particles. Since particulate matter differs greatly as to shape, density, and tendency to break or agglomerate, the ingenuity and experience of the person(s) making the analysis must be applied in selecting a specific measurement procedure. The procedure followed shall be explained in detail in the test report. Operator experience in making size analysis measurements is necessary to obtain reliable results.

4.2.2 Electrical Power Consumption Measurement Equipment. Industrial type voltmeters, ammeters, and wattmeters with specified accuracy shall be used. Refer to PTC 19.6, Electrical Measurements in Power Circuits.

4.2.3 Weighing Equipment. Platform scales or similar weighing equipment with sensitivity of at least 0.2% of the net weight and with accuracy within ±0.5% shall be used.

4.3 METHOD OF MEASUREMENT

PTC 38 and this Code contain the information required for the proper selection of the instrumentation, methods of measurement, and the test procedures to be used for obtaining valid test results under various test situations.

4.3.1 Designation of Test Equipment. Appendix C of PTC 38 contains illustrations of basic sampling system configurations which are recommended by this Code for various applications. Options are provided, in respect to both the filtration section and the gas flow control section of the train, to meet various test requirements. These options may be supplemented by additional requirements and/or guidelines appropriate to the nature of the test.

4.3.2 Designation of Methods of Test. After a study has been made of all the factors involved in conducting a test on a specific installation under the desired operating conditions, the following factors should be utilized to define the nature of the test program which will provide the most valid and meaningful test results:

(a) operating conditions of the plant and the particulate matter collection equipment during the test;

(b) number and duration of test runs;

(c) description of sampling equipment to be used;

(d) number and location of sampling points;

(e) methods for obtaining data;

(f) supplementary test data required and the means for obtaining such data;

(g) procedures for handling test data and reporting test results;

(h) manner of interpretation of test results.

4.3.3 Isokinetic Sampling. PTC 38 contains information on isokinetic sampling and aids for establishing and maintaining isokinetic flow rates.

4.3.4 Overall Mass Collection Efficiency and Fractional Efficiency Measurements. The recommended method for the greatest accuracy in determining overall mass collection efficiency of the equipment is measurement of the inlet and outlet particulate matter concentrations by sampling trains operating simultaneously. With high efficiency collection equipment, the sampling time at the outlet might be more than 1 hr. A few preliminary runs to determine the required sampling time of the inlet and outlet sampling trains are recommended. The operating time for the inlet sampler might be shorter due to more rapid buildup of particulate matter on the filter. Extended sampling time may be possible by selection of a smaller sample nozzle size for the inlet collection. If this is not effective, then multiple measurements may be made at the inlet so that a time average of the inlet measurements over the outlet sampling period may be determined.

Particle size measurements, as described in para. 4.2.1, are to be performed as separate tests from the overall mass efficiency measurement. Impactors are not intended to give total mass loading.

The fractional efficiency is determined by a size analysis of the particulate matter at the inlet and the outlet. The most commonly used method is in-situ sampling with cascade impactors. By weighing each of the stages which collect progressively finer particles, the particle size distribution can be determined. From these distributions, the fractional mass-collection efficiency within each size range can be determined (see Section 5). To obtain particle size distribution in the submicron range, the so-called "diffusion battery" has been used with some success. This method has been combined with impactors to give size distribution over a range from 0.01 micron to 10 microns.

It is advisable to perform preliminary runs to make sure that the stages and filters are not underloaded or overloaded with particulate matter.

In certain cases, particle size analysis of the collected sample can be performed in a laboratory (see PTC 28).

4.3.5 Pressure Drop. Pressure drop is a performance parameter for most particulate matter collection equipment.

When pressure drop across the equipment is measured, i.e., from the inlet flange to the outlet flange, the following precautions must be taken:

(a) ensure that the measurement is taken where the gas flow is relatively uniform (see PTC 38);

(b) ensure that the methods utilized for measurement have taken into consideration the differences between the two measurement stations. These differences could be in configuration and/or in gas flow characteristics, e.g., different cross section and/or different gas density, respectively (see para. 5.3.1);

(c) ensure that repeated measurements are made at each cross section and the values averaged. On installations with equal inlet and outlet cross section and relatively uniform velocity distribution, the pressure drop can be measured directly by a single manometer connected between inlet and outlet flanges (see para. 5.2);

(d) ensure that the manometers used have sufficient sensitivity for the pressure differential to be measured.

4.3.6 Flow or Capacity Measurement. The collection equipment is commonly specified to have a certain capacity in terms of throughput flow rate. The inlet and outlet flow rates will be determined as part of the determination of the inlet and outlet particulate concentration (see PTC 38).

A comparison of these two measurements will give an indication of measurement accuracy and/or the amount of gas leakage into or out of the collector. Gas lost to or gained from the ash conveying systems, insulator purge systems for electrostatic precipitators, and/or bag cleaning air in baghouses must also be taken into account.

Actual gas flow rates together with pressure drops are performance indicators for most collection equipment.

4.3.7 Temperature Drop. On certain collection equipment operating in a dry state, i.e., electrostatic precipitators and baghouses, a maximum allowable temperature drop across the device is often specified.

The best method for obtaining the temperature drop is to utilize the temperature data from the velocity pressure traverses made in the inlet and the outlet ducts of the collection device during the determination of the flow rate through the equipment. Arithmetic averaging of the temperature data will yield realistic temperature drop values. The issue of boundary layer temperatures and duct inner wall temperatures and their effect on the temperature averaging is subject to pretest agreement by the parties to the test (e.g., ignoring low wall temperatures as long as they are above a certain minimum).

If there is significant heat loss between the sampling point and the collection equipment (e.g., uninsulated duct), temperature measurements at the inlet and outlet of the collection equipment should be performed. The temperature measurements shall be performed during the particulate matter sampling period.

4.3.8 Electrical Power Consumption Measurements. The methods suitable for measuring the power consumption of the main equipment and any auxiliaries are adequately covered in other ASME publications. For the consumption of electrical energy, refer to PTC 19.6, Electrical Measurements in Power Circuits.

The specifications under which the collection device has been engineered normally specify the power consumption, which is considered a parameter of performance. This includes the primary power to an electrostatic precipitator, pump power for a scrubber, reverse gas fan power for a baghouse, and auxiliary power for the equipment.

The power consumption measurements shall be performed during the sampling and flow measurement period.

SECTION 5 — COMPUTATIONS

5.1 INTRODUCTION

This Section deals with three main computations for the performance of particulate matter collection equipment:

(a) formulas for both overall and fractional collection efficiency;

(b) formulas for equipment pressure drop;

(c) procedures for uncertainties with respect to both validity of data and accuracy of results.

5.2 COMPUTATION OF COLLECTION EFFICIENCY

5.2.1 Overall Mass Collection Efficiency. If the gas mass flow rate and particulate matter concentration are known at the inlet and outlet of the particulate collection equipment, the total mass of the particulate matter may be calculated to determine the overall mass collection efficiency E, as in Eqs. (1) and (2).

$$E, \% = \left[\frac{G_{tD_1} - G_{tD_2}}{G_{tD_1}}\right]100 \qquad (1)$$

where

$$G_{tD_n} = C_{G_n}(G_{tf_n}) \qquad (2)$$

and

n = 1 for inlet and 2 for outlet

C_{G_n} = particulate matter concentration at the inlet or outlet of the collector (unit mass/unit mass flue gas)

E = overall mass collection efficiency (percent)

G_{tD_n} = total particulate matter (unit mass/unit time)

G_{tf_n} = weight of flue gas (unit mass flue gas/unit time)

When the particulate matter mass concentration is expressed per unit gas volume, the conversion to C_{G_n} is

$$C_{G_n} = \frac{C_{t'n}}{\rho_{f_n}} \qquad (3)$$

where

$C_{t'n}$ = particulate matter concentration at inlet or outlet of the collector (unit mass per unit gas volume)

ρ_{f_n} = density of gas at standard dry conditions (unit mass per unit volume)

In those special cases when the volumetric gas flow at the inlet and outlet are considered the same, Eq. (4) may be employed, utilizing particulate matter concentration measurements obtained from both the inlet and outlet of the particulate matter collection equipment.

$$E, \% = \left[\frac{C_{t'1} - C_{t'2}}{C_{t'1}}\right]100 \qquad (4)$$

5.2.2 Fractional Mass Collection Efficiency. The particle size distribution is usually represented graphically on logarithmic-probability paper, with Stokes particle diameter on the logarithmic scale (log scale) versus cumulative percent by mass less than or greater than the stated size on the probability scale (see Fig. 1).

(a) Based on the particle size distribution at the inlet and outlet of the collection equipment, efficiency for particles larger than a certain size can be calculated as follows.

$$E_{+D} = \frac{S'_{+D} - \dfrac{G_{tD_2}}{G_{tD_1}} S''_{+D}}{S'_{+D}}(100) \qquad (5)$$

or

$$E_{+D} = \frac{S'_{+D} - \dfrac{100 - E}{100} S''_{+D}}{S'_{+D}}(100) \qquad (6)$$

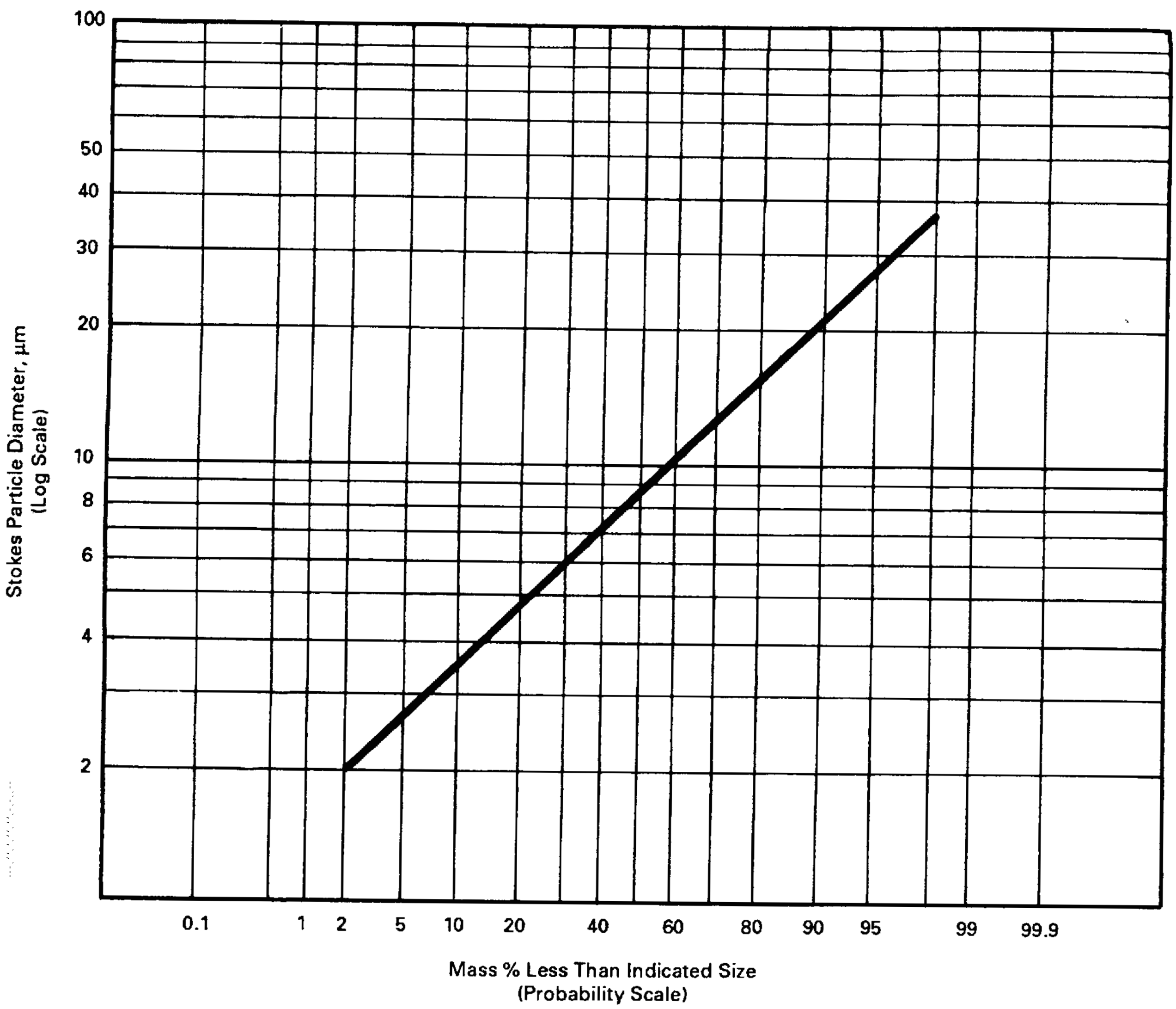


FIG. 1 TYPICAL PARTICLE SIZE DISTRIBUTION CURVE

Fractional efficiency between two particulate sizes D_1 and D_2 can be calculated as follows.

$$E_{-D_2+D_1} = \frac{S'_{-D_2+D_1} - \dfrac{G_{tD_2}}{G_{tD_1}} S''_{-D_2+D_1}}{S'_{-D_2+D_1}} (100) \quad (7)$$

It can be shown that $G_{tD_2}/G_{tD_1} = (100 - E)/100$. Thus

$$E_{-D_2+D_1} = \frac{S'_{-D_2+D_1} - \dfrac{100 - E}{100} S''_{-D_2+D_1}}{S'_{-D_2+D_1}} (100) \quad (8)$$

where

E_{+D} = efficiency of equipment in removal of particles with diameter larger than D, %

$E_{-D_2+D_1}$ = efficiency of equipment in removal of particles with diameter larger than D_1 and smaller than D_2 (Note: $D_2 > D_1$), %

S'_{+D} = percentage by weight of the particles of diameter larger than D at the inlet of the equipment, %

S''_{+D} = same as S'_{+D} except at the outlet of the equipment

$S'_{-D_2+D_1}$ = percentage by weight of the particles of diameter larger than D_1 and smaller than D_2 at the inlet of the separator, %

$S''_{-D_2+D_1}$ = same as $S'_{-D_2+D_1}$ except at the outlet of the separator

D = particle diameter [customarily given in μm (10^{-6}m)]

(b) If an overall efficiency guarantee has been made based on a specified size analysis of the particulate matter entering the collection equipment, then the efficiency corrected to this size analysis may be calculated as follows.

$$E_{corrected}, \% = (E_{+50}S'_{+50} + E_{-50+30}S'_{-50+30} + E_{-30+10}S'_{-30+10} + E_{-10+5}S'_{-10+5} + E_{-5+1}S'_{-5+1} + E_{-1}S'_{-1})\left(\frac{1}{100}\right) \quad (9)$$

Note that the S values in Eq. (9) are estimated or specified before the test, while the E values are the actual measured values. The numerical values of the subscripts given in Eq. (9) are an example; any other set of particle diameters can be utilized as per the pretest determination.

5.2.3 Other Particulate Matter Collection Equipment Performance Criteria. For a variety of reasons, performance criteria other than (or at times in addition to) those described in paras. 5.2.1 and 5.2.2 are often required.

(a) In solid or liquid fuel burning boilers, it is often required that the average particulate matter loading in the flue gas leaving the collection equipment shall not exceed a given level of particulate mass per unit of heat input or per unit volume of gas leaving (corrected to a specified gas composition), while burning a given type of fuel (e.g., coal plus fuel oil, for which all analyses are defined). See PTC 38, Section 5.

There may be additional requirements regarding the opacity of the flue gas.

(b) In the case of wet scrubbers, where the mass of the flue gas is changed during the scrubbing process, the performance requirement can be expressed in terms of the average mass of particulate matter per dry volume of the gas leaving the collecting equipment, sometimes corrected to 12% CO_2 by volume.

5.3 EQUIPMENT PRESSURE DROP

The performance of particulate matter collection equipment is also evaluated by the measured average total pressure drop through the equipment. The total pressure drop is directly related to the equipment energy consumption and, for some types of equipment, is correlated with the particulate collection efficiency; e.g., cyclones and wet scrubbers (see Appendix B).

5.3.1 Necessary Conditions. The selection of pressure drop calculation method depends upon which of the following conditions can be complied with:

(a) work performed on the system does not exceed 1% of the system total loss of power due to the pressure drop;

(b) heat lost or gained by the system is not more than 5% of the flue gas internal energy, or 5% with respect to the flue gas heat content;

(c) the extent of permitted deviation from steady state is a function of the actual method of measurement and must be determined on a case-by-case basis; however, changes affecting the flue gas

rate less than 5% during the measurement can be considered as steady state for the purpose of pressure drop measurement;

(d) the flue gas mass, average velocity, and density can be considered the same for both measurement stations as long as the measured difference between them is less than ±10%.

5.3.2 Total Pressure Drop — Static Pressure Method. Providing that all the conditions in para. 5.3.1 are met, the total pressure drop can be found by

$$(\Delta P_t)_{1-2} = (\Delta P_{sg})_{1-2} + (Z_1 - Z_2)(\rho_f - \rho_t)\left(\frac{g}{g_c}\right) \quad (10)$$

where, in consistent units,

$(\Delta P_t)_{1-2}$ = total pressure drop
$(\Delta P_{sg})_{1-2}$ = static pressure drop
ρ_f = average gas density at duct conditions
ρ_t = average density of the fluid (gas) in the tubes connecting the static probes to the instrument which measures the $(\Delta P_{sg})_{1-2}$
Z_1, Z_2 = height of the static probe port above a common reference
g = gravitational acceleration
g_c = gravitational conversion factor

The measurement is performed with the two static probes connected to an instrument or a device which measures $(\Delta P_{sg})_{1-2}$ directly.

If the measurement of the static pressure differential between the inlet and the outlet of the particulate collection equipment is done with two separate instruments (one for the inlet and one for the outlet), and the instruments are adjacent to their test ports, then in Eq. (10) replace ρ_t by $\bar{\rho}_{ambient}$, and replace static pressure drop $(\Delta P_{sg})_{1-2}$ by $(P_{sg})_1 - (P_{sg})_2$. Therefore, Eq. (10) becomes

$$(\Delta P_t)_{1-2} = (P_{sg})_1 - (P_{sg})_2 + (Z_1 - Z_2)(\rho_f - \bar{\rho}_{amb})\left(\frac{g}{g_c}\right)$$

5.3.3 Total Pressure Drop — Total Pressure Method. In cases where only velocity varies among the conditions in para. 5.3.1, and the density can be considered the same for both stations, then the total pressure drop can be found by

$$(\Delta \bar{P}_t)_{1-2} = (\bar{P}_t)_1 - (\bar{P}_t)_2 + \bar{\rho}_f(Z_1 - Z_2)\left(\frac{g}{g_c}\right) \quad (11)$$

where

$$\bar{P}_t = \bar{P}_{sa} + \frac{1}{2g_c}\bar{\rho}_t \bar{V}^2 \quad (12)$$

and

$$P_{sa} = P_{sg} + P_b \quad (13)$$

In consistent units,

$\bar{P}_t$ = average total pressure, lbf/ft^2
$\bar{P}_{sa}$ = absolute static pressure, lbf/ft^2
P_{sg} = gage static pressure, lbf/ft^2
P_b = barometric pressure, lbf/ft^2
$\bar{V}$ = average gas velocity, ft/sec
$\bar{\rho}_f$ = average flue gas density, lbm/ft^3

Note that on systems with large differences in elevation between the measurement stations, the barometric pressure should be measured at each station and the respective values inserted in Eq. (13) for stations 1 and 2.

5.3.4 Total Pressure Drop — General Total Pressure Method. Thermodynamic analysis utilizing the First Law and the concept of enthalpy can be utilized to deal with a situation where none of the conditions listed in para. 5.3.1 are valid. This type of analysis is beyond the scope of PTC 21. For particulate collection equipment, the methods of paras. 5.3.2 and 5.3.3 are sufficient. In the case of work performed on the system (e.g., accelerating droplets, etc.), this work is usually an integral part of the system particulate collection process and therefore should be part of the energy balance as expressed by the total pressure drop. A detailed discussion is included in Appendix C.

5.4 VARIATION OF TEST RESULTS — OUTLIERS

According to Daniel and Wood (Section 7, ref. 1), "most large collections of data, and occasionally even small collections, contain a few 'wild points,' sometimes called mavericks or outliers. What happened to make them nontypical cannot usually be reconstructed. They must be spotted, however, since to retain them may invalidate the judgments we make."

TABLE 2 STATISTICAL VALUE OF DATA POINTS (DEVIATION VS PROBABILITY)

T [Note (1)]	P_θ [Note (2)]	N [Note (3)]
1.5	0.8664	4
1.55	0.8789	4
1.6	0.8904	5
1.65	0.9011	5
1.7	0.9109	6
1.75	0.9200	6
1.8	0.9281	6
1.85	0.9357	8
1.9	0.9426	8
1.95	0.9488	10
2.0	0.9545	10
2.1	0.9643	10
2.2	0.9722	20
2.3	0.9786	20
2.4	0.9836	20
2.5	0.9876	50
2.6	0.9907	50
2.7	0.9931	50
2.8	0.9949	100
2.9	0.9963	100
3.0	0.9973	500
3.5	0.9995	500
4.0	0.9999	500

NOTES:
(1) T is ratio of deviations from calculated mean value of standard deviation.
(2) P_θ is probability of occurrence (area under the normal distribution curve, between $Y = \pm T$).
(3) N is number of data points (N must be ≥ 4).

5.4.1 Criteria for Determining Outliers. When there are no obvious errors (i.e., obvious process upsets, instrument malfunctions, or calculation errors), an analysis of outliers may be useful.

(a) Imbalance Beyond a Calculated Criterion. If a balance equation (e.g., mass balance) can be utilized to check the test results and if, after considering the testing errors, most results are in agreement with the balance equation, then a test result which is in disagreement may be an outlier. For example, the combustion stoichiometric calculation and O_2 measurement indicate the gas mass flow rate. If any measurement of velocity, temperature, pressure, or O_2 yields a result which is greatly different, then that result could be an outlier.

(b) Exceeding a Statistical Criterion. CAUTION: This method should be applied only to the average result obtained when performing the test. For example, if a given duct cross section is divided into several subsections for the purpose of measuring the velocity profile, temperature, particulate matter concentration, and major gas composition (as per the recommended procedure in PTC 38), only the *average* value of the velocity, temperature, or particulate matter concentration, etc., is to be utilized when analyzing for outliers. Hence, the number of cases evaluated statistically is the number of complete tests performed.

A number of statistical methods for setting limits for point rejection exist (see PTC 19.1, Measurement Uncertainty). One of those methods, Chauvenet's Criterion, is reviewed below because of its applicability to particulate matter determination. It is assumed that the errors are normally distributed such that Table 2 can be utilized to find probability values. *A statement of the criterion is:* Any reading of a series of N readings shall be rejected if the magnitude of its deviation from the true or mean value is such that the probability of occurrence of such deviation does not exceed P_θ from Table 2, where

$$P_\theta = 1 - \frac{1}{2N} \tag{14}$$

and

N = number of data points (N must be ≥ 4)
P_θ = probability of occurrence

Upon calculation of P_θ [Eq. (14)], the value of the dimensionless T should be found from Table 2. T is the ratio of the deviation from the calculated mean value to σ

$$T = \frac{|X_n - \overline{X}|}{\sigma} \tag{15}$$

where

X_n = actual value of each of the data points
$\overline{X}$ = mean value of all X values
σ = standard deviation (see PTC 19.1)

This value of T should not be exceeded for any point among the N data points. To obtain T_{cal}, i.e., the value of the calculated T for the sample, the estimated standard deviation S is required.

$$S = \left[\frac{\sum_{n=1}^{N} (X_n - \overline{X})^2}{N - 1}\right]^{1/2} \tag{16}$$

or

$$S = \left[\frac{\sum_{n=1}^{N} X_n^2 - \frac{\left(\sum_{n=1}^{N} X_n\right)^2}{N}}{N - 1} \right]^{1/2} \tag{17}$$

where

$$\overline{X} = \frac{\sum_{n=1}^{N} X_n}{N} \tag{18}$$

Finally, to check for outliers

$$T_{cal} = \frac{|X_n - \overline{X}|}{S} \tag{19}$$

If $T_{cal} > T$ in Table 2, the datum point is an outlier.

The user of this method is cautioned that the procedure should be done only once; i.e., after eliminating the outliers, the procedure should *not* be repeated again with a new N. As previously noted, this method should not be utilized unless $N \geq 4$.

5.5 ERROR ANALYSIS

5.5.1 General. For most particulate matter collection equipment, performance tests are done by one of the following two methods.

(a) *Point Source Testing.* Traversing of the duct up and downstream of the equipment is necessary in order to establish average flue gas flow rate, average total pressure, and average particulate matter concentration. Temperature, O_2, and velocity are measured simultaneously and at each point. These tests are usually performed only a few times and always under somewhat different test conditions.

(b) *Continuous Monitoring.* The measurements are performed continuously or at a prescribed frequency. The instrument and the data recording systems (and at times, the data reduction systems as well) are such that a very large number of tests are performed, e.g., opacity monitoring in a stack.

The true value of the measured variable is never known. However, an error analysis which is aided by calculated criteria [see para. 5.4.1 (a)], experience, and common sense can provide an acceptable estimation of the true value of the measured variable.

Method A presents a problem in performing an error analysis when it results in only two or three tests. It should be established prior to the actual test which type of error analysis, if any, shall be performed, and what will constitute an acceptable "true value." The results obtained through Method B can be analyzed by random error analysis; see PTC 19.1.

5.5.2 Glossary

accuracy — closeness of agreement between a measured value and the true value

average value $\overline{X}$ — arithmetic mean of N readings [see Eq. (18)]

bias β — difference between the average of the measurement population and the true value. The true systematic or fixed error which characterizes every number of any set of measurement in the population.

measurement error — difference between the true value and the measured value. It includes both bias and precision error.

mistake — divergence arising from an unintentional departure from the usual procedure, e.g., a misreading of scale, etc. (from Section 7, ref. 5)

parameter — quantity such as temperature or pressure used in deriving a result

precision error — random error based on a set of repeated measurements

result r — value calculated from a number of parameters

sample size N — number of individual measurements of a parameter in a sample

sensitivity — ratio of the change in a result to a change in a parameter

5.5.3 Maximum Error. When random error analysis is impractical due to the limited number of tests, i.e., very small sample size N, maximum error analysis can be performed. Theoretically, maximum error analysis is all inclusive (i.e., bias error, precision error, and mistakes) and generates error-band width which often leads to a large overestimate of the error. However, prior to the actual maximum error analysis, all efforts should be made to reduce, if not eliminate, the bias errors and the mistakes.

The maximum error is determined for a given result r by

$$\Delta r_{max} = \pm \left[\left| \frac{\partial r}{\partial X_1} \Delta X_1 \right| + \left| \frac{\partial r}{\partial X_2} \Delta X_2 \right| + \ldots + \left| \frac{\partial r}{\partial X_N} \Delta X_N \right| \right] \tag{20}$$

where

$r = f(X_1, X_2, \ldots, X_N)$, and the absolute values are required since $\Delta X_{1 \ldots N}$ is usually $\pm \Delta X_{1 \ldots N}$

The values for the ΔX_n can be established for the specific test or be developed based on past experience. Actually, if estimated standard deviation is available, $\Delta X_n = 3S_n$ can be utilized. [See Eq. (16) or (17), and PTC 19.1.]

5.5.4 Random Error Analysis. The random error is determined for a given result r by

$$S_r = \pm \left[\left(\frac{\partial r}{\partial X_1} S_{X_1} \right)^2 + \left(\frac{\partial r}{\partial X_2} S_{X_2} \right)^2 + \ldots + \left(\frac{\partial r}{\partial X_N} S_{X_N} \right)^2 \right]^{1/2} \tag{21}$$

See PTC 19.1 for the method of obtaining the S_{X_n}.

5.5.5 Conclusion. The subject of error analysis as it applies to particulate collection equipment is addressed in PTC 21 only to the extent necessary for the practical application of this Code. The variety of methods and instruments involved in the measurement of particulate collection equipment performance (particulate matter load, static and dynamic pressures, temperatures, and flue gas composition) renders the detailed and complete treatment of the subject outside the scope of PTC 21.

SECTION 6 — REPORT OF RESULTS

6.1 IMPORTANCE OF REPORTS

6.1.1 Most of the tests conducted in accordance with this Code are performed to obtain data on process emissions or the performance of emission control systems for operational, commercial, and/or regulatory purposes. Therefore, establishing the accuracy and assuring completeness of the test reports are of the utmost importance.

The test report may be subject to scrutiny with respect to the nature and conduct of the tests performed. The actual test data will probably be correlated with the design and operation of the emission source and emission control systems involved. Often tests conducted for one particular purpose are later utilized to provide useful information differing in application from that for which the test was originally conducted.

6.1.2 The purpose of this Section of the Code is to provide guidance with respect to that information which should be obtained during the test program and to recommend formats for recording this information and presenting it in a suitable manner to meet the strict requirements cited above.

6.2 REPORTS AND THEIR CONTENT

A properly conducted test program should result in a final test report containing the following information in a well-organized format, as complete and accurate as possible:

(a) reason(s) for conducting test and the information desired from the test results;

(b) description of the particulate matter collection equipment being tested, with data covering both the source itself (e.g., boiler, incinerator) and all equipment or other factors which may directly or indirectly affect test results (e.g., electrostatic precipitator, fans, duct configuration);

(c) operating conditions of the emission source and all the other equipment and systems listed above, including the nature and flow rates of all material consumed and/or emitted during the test period;

(d) identification and description of the sampling train and test procedures used, with information regarding the basis of their selection;

(e) outline of the manner in which the tests were conducted, with commentary on any deviation from normal action which may have been necessary; include calibration procedures;

(f) test results — both the detailed tabulation of data taken during the test and the calculated test results obtained therefrom;

(g) summary of test results correlated with pertinent operating data and other factors involved. Commentary on the test results and their significance may or may not be required, depending upon the nature of the test assignment.

6.3 RECOMMENDED REPORTING PROCEDURES

The following is presented as a guide for obtaining and presenting the data necessary to fulfill the test objective. These recommendations apply to a typical efficiency and emission test program. The great variation in the nature and conditions of any specific test program may necessitate deviation from these recommended procedures. However, in all cases, the reporting procedure should be so planned and carried out as to achieve the requirements of the above stated criteria for the final test report.

6.3.1 Presurvey Report. In order to properly plan the test program, a preliminary survey of the emission source and the test site should be made. The information obtained during this presurvey should provide considerable help in the selection of the proper testing procedures to be employed and the preparation of a well-organized test plan.

The presurvey should include the acquisition of data on the design, operation, and physical arrangement of the particulate matter collection equipment and the related equipment of concern. These data can be obtained from a study of pertinent design and operating data available from the owner, operator, and vendors involved, plus actual inspection of the test area. The availability and usefulness of installed instrumentation, including meteorological equipment, should also be investigated.

The use of a questionnaire or presurvey report form, suitable for the type of emission source involved, can be very helpful. Samples of such forms for combustion sources, incinerators, and industrial processes are shown in PTC 38. These forms should be augmented by appropriate process flow diagrams and scaled plan and elevation drawings of the equipment involved, including the actual sampling site. A cross section drawing of the duct or stack at the sampling locations, showing exact location of sampling ports, should be prepared. Actual sample point locations should be added to this when determined.

6.3.2 Gas Flow Measurement, Sampling, and Analytical Data. The wide variation in the type of source to be tested, the nature and conditions of the test, and the test procedures employed necessitate a wide variation in the format of the data sheets and report forms required. Typical forms for gas velocity and volume data, field sampling meter data, and analytical data for the samples collected, fuel burned, etc., are included in PTC 38.

The data taken should not be limited to that which may seem essential to the current objectives of the test program. Any supplementary data and observations which may later be useful (e.g., evaluating data for outliers) should be included to the maximum extent practical.

6.3.3 Operating Data. The wide variation in the type of particulate matter collection equipment to be tested and the nature and conditions of the test necessitate a wide variation in the format of the forms needed to record and report operating data. Typical forms for boilers, incinerators, and industrial processes are included in PTC 38. They should be supplemented by similar forms covering the detailed operating data for the other systems and equipment involved in the test — emission control systems, gas flow systems, etc.

6.3.4 Calculations. The calculation procedures used to compute the final test results are an important part of a test report. The test procedures used, the conditions of the test, and the computation facilities available can vary greatly and will determine the methods of calculation and their presentation in the report. The calculation section of a test report may vary in format, ranging from a computer printout of test data and calculated results, accompanied by an example of a typical set of calculations, to a complete set of manually performed calculations presented on appropriate forms.

The primary criteria in presenting calculations in a test report are that the nomenclature and units of measurement used are defined and that the sources of all input data, formulas, constants, and conversion factors are clearly identified. Section 2 of this Code contains a Table of Terms (Table 1) which should be utilized to the maximum extent possible in the tabulation of test data and the calculation and presentation of test results.

6.3.5 Emission Data. Both a detailed report of the calculated efficiencies and emission data obtained during the test, with a summary of the test results, correlated with pertinent operating parameters, are usually required in the final test report. Typical forms for presenting detailed emission data from a combustion source and for presenting a summary of test data, correlated with pertinent operation data, are shown in PTC 38. Both are subject to considerable variation to meet the requirements and conditions of a specific test program.

6.3.6 Responsibility for Test Results. Depending upon the nature and requirements of the test program, it may be necessary to assign the responsibility for obtaining valid test data and preparation of the reports to a specific party or parties. If this is the case, the final test report should be certified or validated in a manner appropriate to the circumstances involved and in accordance with the mutual agreements of parties concerned. In all cases, the final test report should clearly identify all the personnel and organizations involved in the conduct of the test and the determination of test results.

SECTION 7 — BIBLIOGRAPHY

[1] Daniel, C., and Wood, F. S., *Fitting Equations to Data*, Wiley-Interscience, 1971.

[2] Schenck, H., and Hawks, R. J., *Theories of Engineering Experimentation*, Hemisphere Publishing Corp., 1979.

[3] Davies, O. L., *Design and Analysis of Industrial Experiments*, Hafner Publishing Co., 1963.

[4] ASME PTC 19.1, "Measurement Uncertainty."

[5] Brooks, E. F., and Williams, R. L., "Flow and Gas Sampling Manual," EPA-600/2-76-203, July 1976.

[6] Brenchley, D. L., et al., *Industrial Source Sampling*, Ann Arbor Science Publishing Inc., 1974.

[7] ASME PTC 38, "Determining the Concentration of Particulate Matter in a Gas Stream."

[8] Perry, R. H., et al., *Chemical Engineers Handbook*, McGraw-Hill Book Co.

[9] ASME PTC 28, "Determining the Properties of Fine Particulate Matter."

[10] McCain, J. D., et al., "Methods for Determining Particle Mass and Size Properties: Laboratory and Field Measurements," *JAPCA*, Dec. 1974, Vol. 24. No. 12, pp. 1172–1176.

[11] Stockham, J. D., and Fochtman, E. G., eds., "Particle Size Analysis," Ann Arbor Science Publishing Inc., 1977.

[12] EPRI Report CS-3388, Project 781-4, "Fine Particle Measurement Handbook," January 1984.

[13] Industrial Gas Cleaning Institute, Inc., Publication EP-7, "Gas Flow Model Studies," October 1980.

[14] Incinerator Institute of America, Bulletin T-6, "Incinerator Testing."

APPENDIX A
TEST CONSIDERATIONS FOR PARTICULATE MATTER COLLECTION EQUIPMENT

(This Appendix is not part of ASME PTC 21-1991.)

There are four basic types of particulate collection devices in general use — cyclones, electrostatic precipitators, fabric filters, and scrubbers. Each device has distinctive features which affect the way in which it should be tested to obtain performance data. The following brief descriptions of operating parameters are intended to specify particular concerns in determining performance for each collection device.

A1 CYCLONE

This type of collector utilizes centrifugal force to extract particulate matter from a rotating gas stream. The collector may be a single large cyclone or a multitude of small (typically 3 in. to 12 in. diameter) cyclones arranged in parallel. Figure A1 shows a typical cyclone tube and its location in the device. Since the principle of operation depends upon centrifugal force, the device performs best at or near the design velocity specified by the manufacturer in terms of the pressure drop across the unit. There is an optimum operation range below which centrifugal force is inadequate to efficiently separate particles from the gas stream.

The efficiency of cyclone collectors is related to the sizes and densities of particles being collected, as shown in Fig. A2. Performance determination must include a size analysis of the entering particles to obtain a size distribution from which to predict performance. Efficiency is determined by comparison of inlet and outlet particulate matter concentrations (see PTC 21, Section 5).

A high volume sampling train capable of collecting large particulate matter samples is used (see PTC 38). This train collects a sufficient amount of the sample for size determination by centrifugal classification per PTC 28.

The parameters usually specified for a given particulate matter collection efficiency are the gas flow rate, the gas density, and the anticipated pressure drop. In order to arrive at the most accurate representation of cyclone operation, tests should be made at or near the design flow rate and temperature.[1]

Test data and results required are as follows:

(a) gas flow rate;

(b) total pressure drop across equipment, inlet to outlet (in most cases, static pressure drop is satisfactory);

(c) inlet particulate matter concentration;

(d) outlet particulate matter concentration;

(e) inlet and outlet particle size distribution required for fractional efficiency determination;

(f) gas temperature;

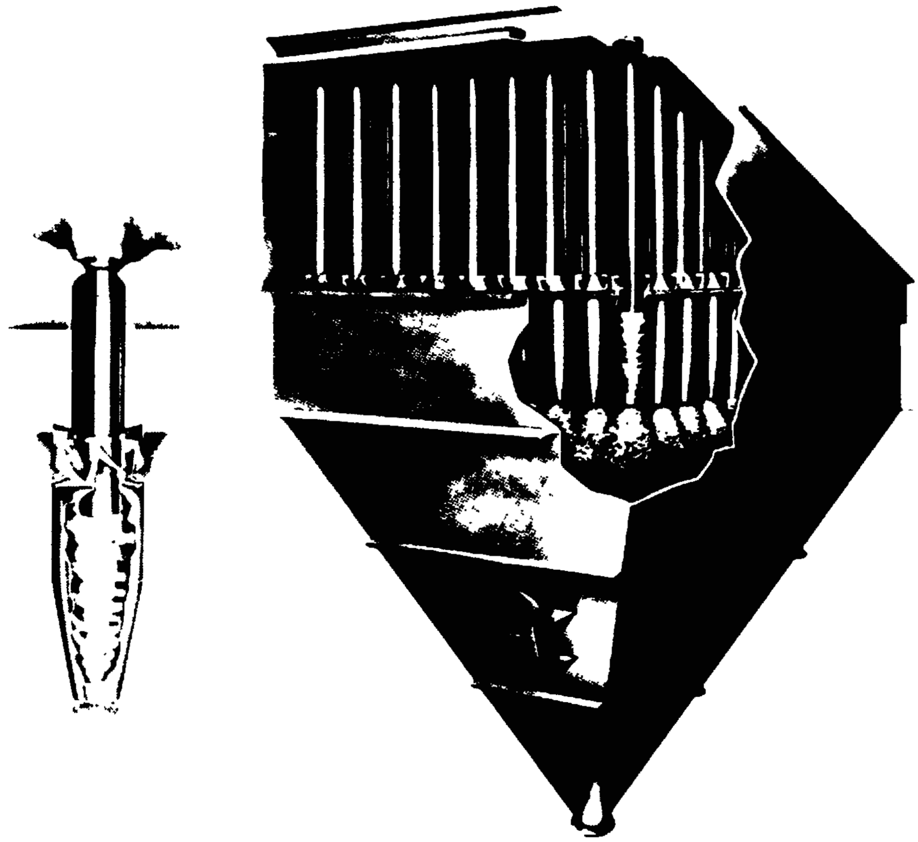
(g) collection efficiency.

A2 ELECTROSTATIC PRECIPITATOR

This equipment uses electrostatic forces to collect particulate matter (see Fig. A3). Gas molecules are ionized by corona current discharge from high voltage electrodes and the particles are subsequently charged so that they will be attracted to the collecting plates.

The efficiency of an electrostatic precipitator is a function of a number of factors, including particle size distribution; the chemical composition of the particulate matter; electrical resistivity; oper-

[1] The pressure drop is affected by density, which is in turn affected by temperature, pressure, and flue gas composition.



GENERAL NOTE: Courtesy Aerotech Industries.

FIG. A1 TYPICAL CYCLONE TUBE AND COLLECTOR ARRANGEMENT

ating voltage and current; inlet and outlet gas flow distribution in the precipitator; and the velocity, temperature, density, and composition of the gas stream.

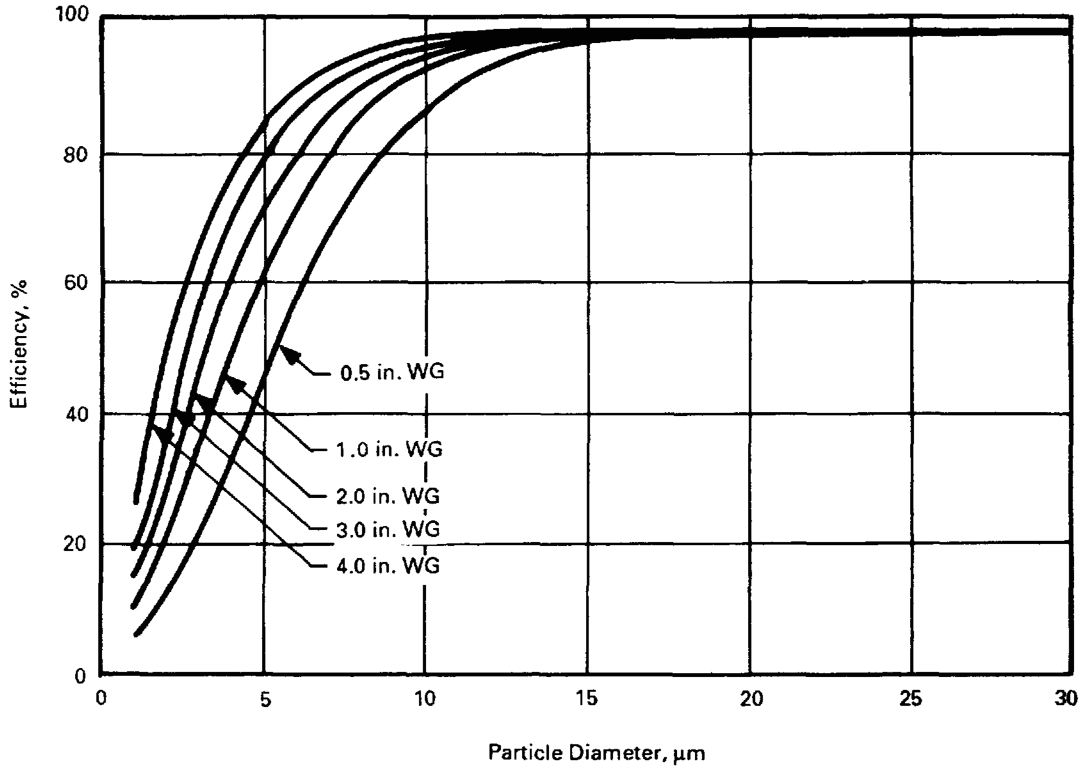
Since performance is affected by the local gas stream velocity, it is important that gas flow rates be as close to design as possible and the gas be distributed across the face of the precipitator as evenly as possible. This is usually accomplished by installing distribution baffles at the inlet and outlet. Acceptable distribution should be confirmed by a field pretest with no power to the electrodes and with air flowing through the precipitator rather than process gas.

Sampling trains are usually low volume, of the type discussed in PTC 38. Since these trains usually employ coincident velocity measurement, isokinetic sampling is easily obtainable. Mass loading is determined by the train, but size distribution should be determined separately by an impactor. The determined size distribution is useful in evaluating precipitator performance. The chemical ash composition should be determined from a sample of the ash collected during the test. Pressure drop is ordinarily low and may not be a significant factor in performance.

Sometimes gas conditioning agents are used to alter the precipitator performance by modifying the gas composition or the electrical resistivity. The quantity of any gas conditioner(s) should be noted in the result so that future comparative tests will be meaningful.

CAUTION: Since the gas stream is ionized, a large potential for electrostatic charge exists. Trains and all measurement probes in both the inlet and outlet location must be well grounded.

Electrostatic precipitators are cleaned by rapping or vibrating the collecting plates and the dis-



GENERAL NOTE:
Efficiencies are shown for a dust concentration of 3.0 gr/ft^3, gas temperatures from 70°F to 700°F, and an ash specific gravity of 2.5.

FIG. A2 BASIC PERFORMANCE CHARACTERISTIC OF TYPICAL CYCLONE COLLECTOR

charge electrodes. The frequency, intensity, and duration of the cleaning procedure will determine the cleanliness of the internal parts. Since particulate matter can be reentrained into the gas stream during cleaning, it is essential that cleaning programs be optimized before tests are done. Cleaning should be continued at the optimum rate during the test.

Electrostatic precipitators are considered constant-efficiency devices; that is, all other things being equal, the precipitator will remove a constant percentage of the incoming particulate matter.

Test data and results required are as follows:

(a) gas flow rate, inlet and outlet;

(b) gas temperature, inlet and outlet;

(c) gas velocity distribution between collecting plates;

(d) pressure drop across precipitator, inlet to outlet, including any flow distribution devices (in most cases, static pressure drop is satisfactory);

(e) inlet particulate matter concentration;

(f) outlet particulate matter concentration;

(g) inlet and outlet particle size distribution (required for fractional efficiency);

(h) power input to transformer/rectifier sets;

(i) power input to auxiliary equipment such as blowers and heaters;

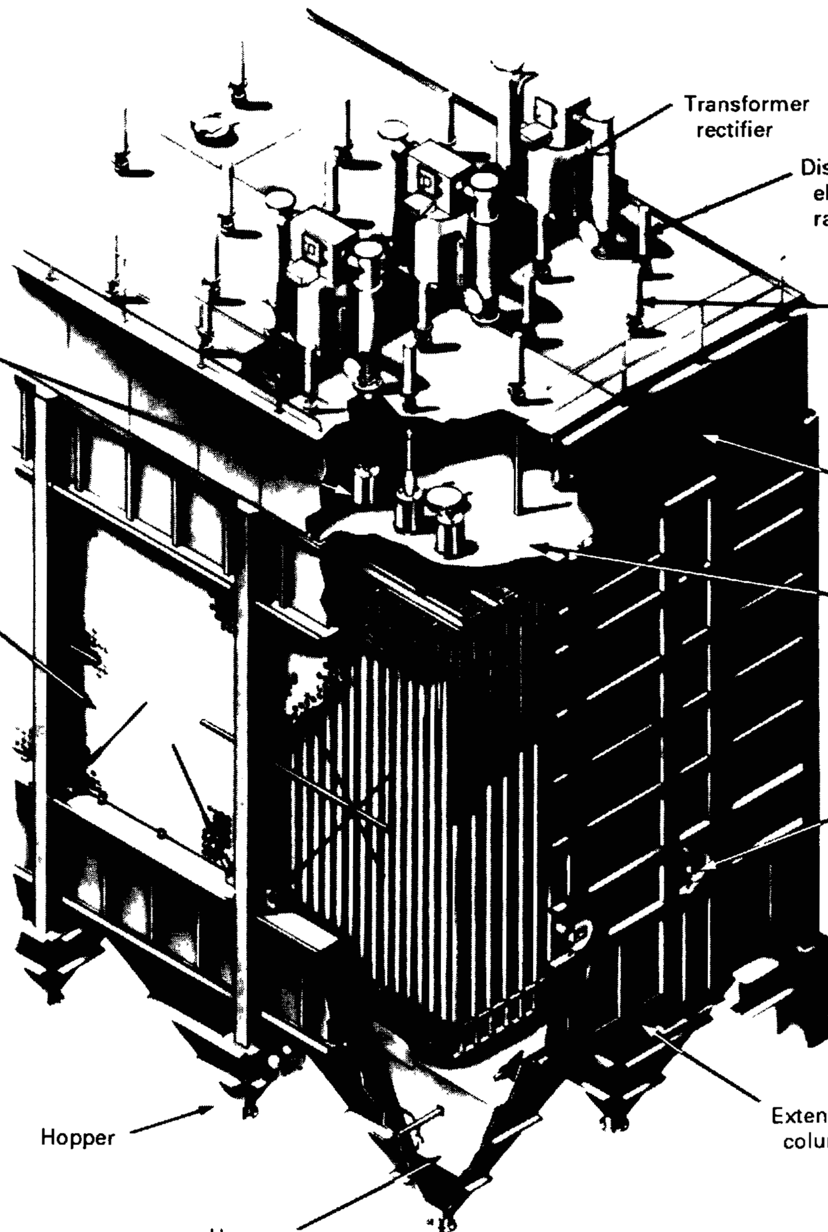
(j) spark rate;

(k) voltage and current of precipitator power supply equipment;

(l) particulate matter composition (elemental ash analysis);

(m) amount and type of gas conditioning agent used;

(n) cleaning factors — frequency, intensity, and



GENERAL NOTE: Courtesy Research-Cottrell.

FIG. A3 TYPICAL WIRE AND PLATE TYPE PRECIPITATOR

duration for both high voltage electrodes and collecting plates;

(o) composition of flue gas (O_2, CO_2, SO_2, SO_3, H_2O);

(p) collection efficiency;

(q) fuel analysis;

(r) ash analysis.

A3 FABRIC FILTER

This equipment uses a filter medium to remove the particles from the gas stream. As shown in Fig. A4, the equipment causes the gas stream to pass through a filter material which retains the particles on the material. The particulate matter may be collected on either the outside or inside surface of the filter medium. The filter medium is usually felted or woven cloth. It provides a substrate on which the particles are collected, and the resultant cake of particulate matter assists in filtering the gas stream. The thickness of the cake affects the performance, so agreement must be reached on the pressure drop across the tubesheet (i.e., through the cloth and cake) to be used during the test. Cleaning frequency and intensity required are a function of inlet particulate matter concentration and pressure drop.

All things being equal, fabric filters are considered constant-emission devices, because the outlet particulate matter loading is more a function of leaks and bleed-through of the fabric than of particulate load. For this reason, collection efficiency of a fabric filter is an unrealistic representation of performance. The true performance indicator is the outlet mass concentration. Therefore, outlet tests are usually sufficient to indicate performance.

Since filter performance is based mainly on physical properties of the particles, it is not necessary to obtain a particulate matter sample for composition analysis. Where desired, impactors are used to collect samples for particle size distribution. The size and shape of the particles will have an effect on the porosity of the filter cake and, hence, the pressure drop across the filter. Gas temperature should be sufficiently above acid dew point to avoid condensation on the cake and filter medium.

Cleaning of the filter medium is accomplished by reversing the flow of gases (or air) through the fabric, shaking the fabric, or a combination of the two. The performance test should reflect the normal cleaning procedures. If a filter is cleaned continuously, the test must be run under the operating conditions of cleaning. If a filter needs to be cleaned only every 12 hr, testing should not include a cleaning cycle. The majority of cases fall between these conditions.

Test sample trains are low volume, as described in PTC 38. Though there are no large electrostatic forces, grounding of sample trains is recommended to avoid the possibility of explosion.

Test data and results needed are as follows:

(a) gas flow rate;

(b) gas temperature, inlet and outlet;

(c) gas-to-cloth ratio;

(d) total pressure drop across filters, inlet to outlet (in most cases, static pressure drop is satisfactory);

(e) pressure drop across tubesheet (cloth and filter cake) of each module;

(f) cleaning procedures — frequency, duration, volume, and pressure of cleaning fluid;

(g) power of auxiliary equipment, such as reverse gas fan and/or air compressor;

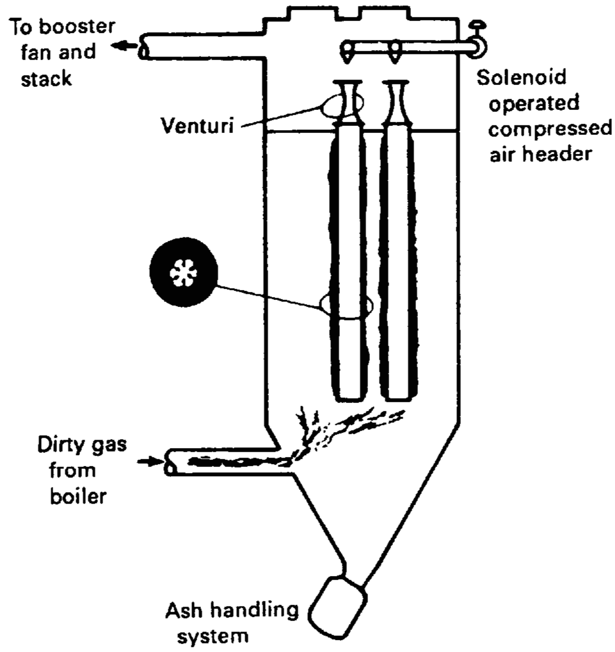
(h) inlet particulate matter concentration (if required);

(i) outlet particulate matter concentration.

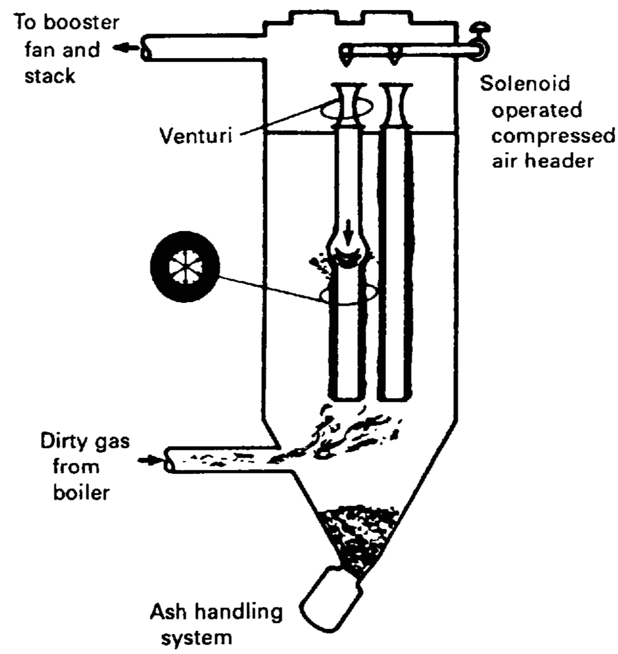
A4 SCRUBBERS

Scrubbers are used to remove particulate matter from a gas stream and, with a chemical solution, to minimize the amount of SO_2 and/or other gaseous constituents in the effluent. Analysis of gas removal performance is beyond the scope of this Code (see PTC 40, Flue Gas Desulfurization Units).

A4.1 In the *wet scrubber*, the flue gases are passed through a contactor (e.g., venturi, packed bed, open spray chamber) where they come in contact with a liquid or a slurry (see Fig. A5). The particulate matter is captured by the liquid through entrapment in droplets, in liquid film, or in liquid bath. The saturated outlet gases and droplets/wet particles pass through a mist eliminator of centrifugal, mesh, or chevron type which minimizes carryover. Mist eliminator performance affects collection efficiency, since many droplets have solid particles entrapped. Some installations reheat the gases or use another source of hot gases to provide buoyancy to the saturated gas stream and to minimize visible plume formation. Outlet measurements for efficiency determinations must be made immediately after the scrubber. Measurements for source

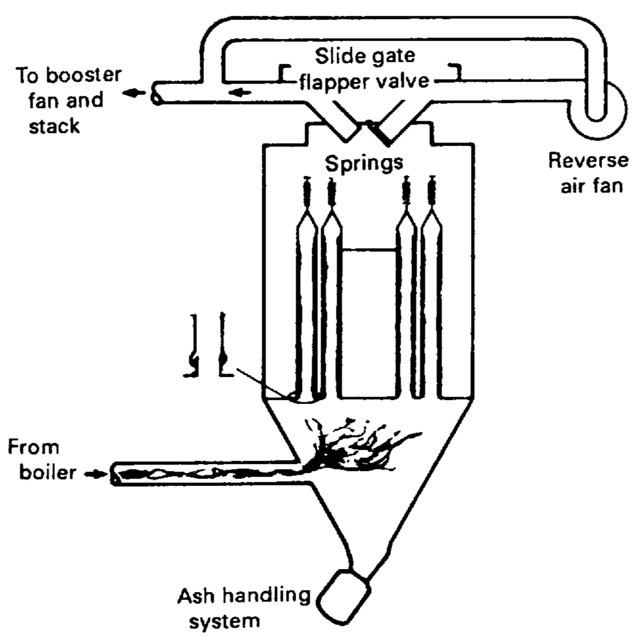


(1) Schematic arrangement of outside collection fabric filter using pulse jet cleaning

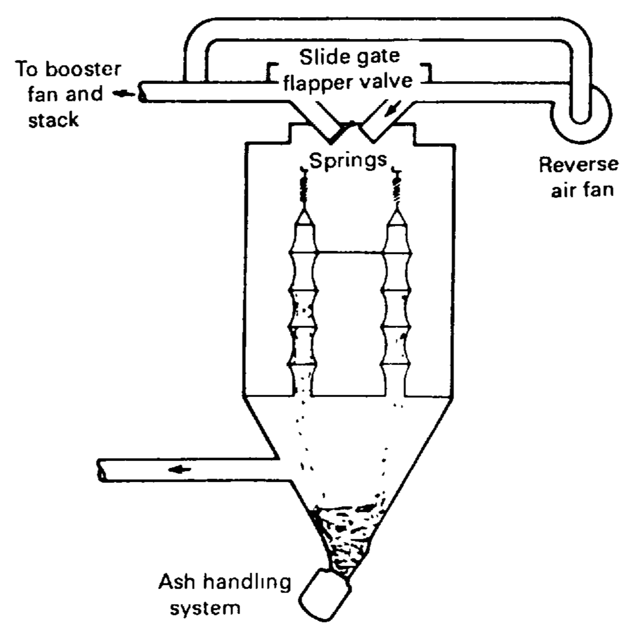


(2) Schematic of pulse jet cleaning operation of outside collection fabric filter

(a) Pulse-Jet Fabric Filter



(1) Schematic arrangement of inside collection fabric filter cleaned by reverse flow



(2) Schematic of reverse air cleaning of inside bag collection fabric filter

(b) Reverse Air Fabric Filter

FIG. A4 TYPICAL FABRIC FILTERS

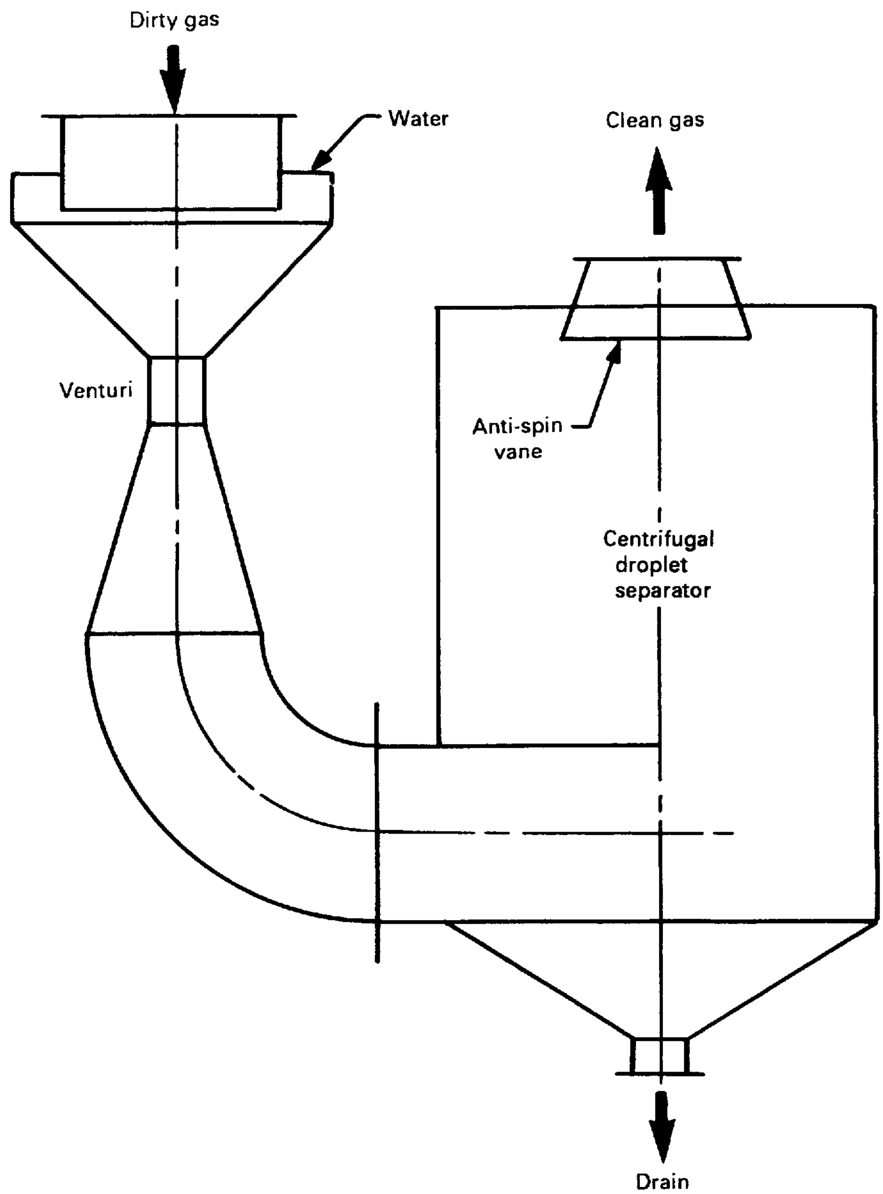


FIG. A5 VENTURI SCRUBBER

emission must be made sufficiently downstream of the confluence of both gas streams to assure non-stratified conditions.

Low volume sampling trains are identified in the Appendix of PTC 38. The interpretation of test results on a saturated gas stream is difficult due to chemical reactions in the sampling equipment. Measurement of particle size distribution in the scrubber outlet before reheat is not practical; inlet particle size distribution is determined by impactor.

The collection efficiency of a wet scrubber is the result of the turbulent contact between the liquid, gases, and particles. This contact is usually a function of the pressure drop across the unit and the pumping power utilized by the scrubber. Depending upon the type of scrubber, a combination of some of the following parameters should be measured.

Test data and results required are as follows:

(a) inlet gas flow rate;
(b) outlet gas flow rate;
(c) inlet gas density;
(d) outlet gas density;
(e) inlet gas temperature;
(f) outlet gas temperature, before and after reheat;
(g) inlet gas humidity;
(h) outlet gas humidity;
(i) energy required for reheat;
(j) liquid or slurry flow rate to scrubber;
(k) pressure drop across scrubber contactor and breechings;
(l) inlet particle size distribution;
(m) outlet particle size distribution after reheat;
(n) power to fan and pumps;
(o) slurry system discharge solids concentration;
(p) liquid make up flow rate;
(q) inlet particulate matter concentration;
(r) outlet particulate matter concentration;
(s) collection efficiency.

A4.2 In a *dry scrubber,* the flue gases are passed through an open spray chamber, where they are contacted by a liquid spray containing sorbents. The quantity of liquid is closely controlled to keep the temperature of the flue gases above the dew point (usually 15–40°F above), to keep the gases, fly ash, dry reaction products, and sorbent in a dry form. A collecting device is added to remove these dry substances from the gases (see PTC 40 for performance measurement during collection of acid gases in a dry scrubber).

When an *electrostatic precipitator* is used, the concentration of input particulate matter to the collection device should be measured downstream of the spray dryer. Outlet particulate concentrations are measured after the collection device. The guidelines in para. A2 for precipitator performance and in para. A3 for fabric filter performance may be used.

A4.3 In *dry injection* systems, sorbents are added to the flue gas upstream of the particulate matter collection device which removes fly ash, dry reaction products, and unreacted sorbent from the gas stream. To determine efficiency, the guidelines in para. A2 for precipitator performance and in para. A3 for fabric filter performance may be used.

APPENDIX B
COMPUTATION OF COLLECTION EFFICIENCY — EXAMPLE

(This Appendix is not part of ASME PTC 21-1991.)

A high efficiency cyclone dust collector was tested with the following results.

Inlet (Station 1)

$Q_1 = 31{,}880$ ACFM
$T_1 = 200°F$
$P_b = 28.5$ in. Hg
$(P_{sg})_1 = -7$ in. WG
$(h_r)_1 = 10\%$ moisture by volume
$M_f = 28$ lbm/lb-mole
$C_{t'_1} = 3.8$ gr/SDCF
$G_{tD_1} = 11.7$ lbm/min

Outlet (Station 2)

$G_{tf_2} = G_{tf_1}$
$T_2 = 195°F$
$G_{tD_2} = 0.5846$ lbm/min
$(P_{sg})_2 = -10$ in. WG
$(\Delta P_t)_{1-2} = 3$ in. WG
$(h_r)_2 \simeq (h_r)_1$

Table B1 depicts the test results and calculated information regarding the particulate matter.

From Eq. (1) of PTC 21, Section 5,

$$E = \left(\frac{11.7000 - 0.5846}{11.7000}\right)(100)$$

$$= 95.0034 \simeq 95\% \text{ total efficiency}$$

NOTE: G_{tD_n} should be calculated using Eq. (2). It is not recommended to sum up the fractional concentrations obtained with a cascade collector, since it may lead to a large error. A comparison of the total particulate loads obtained from the cascade collectors to that obtained when total concentration was measured is recommended.

If E_{+15} is to be determined using data from Table B1, Eq. (6) can be used as follows:

$$S'_{+15} = 20 + 3 + 5 + 4 = 32.0\%$$

$$S''_{+15} = 2.0 + 0.31 + 0.513 + 0.41 = 3.233\%$$

$$E_{+15} = \frac{32 - \left[\left(\frac{100 - 95}{100}\right)(3.233)\right]}{32}(100) = 99.495\%$$

If the fractional efficiency E_{-10+5} is required, Eq. (8) can be used as follows:

$$E_{-10+5} = \frac{37.5 - \left[\left(\frac{100 - 95}{100}\right)(68.1)\right]}{37.5}(100) = 90.920\%$$

If required, the values of C_{G_n}, $C_{t'_n}$, and G_{tf_n} can be found from the above information, although these values were required already in order to develop part of Table B1:

$$\rho_{\text{std dry}} = \frac{M}{386.7} = \frac{28}{386.7} = 0.0724 \text{ lbm/SDCF}$$

From Eq. (3):

$$C_{G_1} = \frac{3.80}{0.0724} = 52.5 \text{ gr/(lbm dry gas)}$$

$(Q_{std})_1 = (Q_1)$ (temperature correction)

× (pressure correction; barometric and inside

the duct) (moisture correction)

$$= (Q_1)\left(\frac{460 + 70}{460 + 200}\right)\left[\frac{28.5 - 7(0.0735)}{29.92}\right](0.9)$$

TABLE B1 CYCLONE TEST RESULTS (PARTICULATE COLLECTION EFFICIENCY)

Particle Size at Inlet, µm	Average Inlet Particle Size, µm	Percent by Mass at Inlet, % (Totals 100%)	Particle Mass at Inlet, lbm/min	Percent by Mass at Outlet, % (Totals 100%)	Particle Mass at Outlet, lbm/min
+ 50	50	4.0	0.4700	0.410	0.0024
−50 + 40	45	5.0	0.5900	0.513	0.0030
−40 + 30	35	3.0	0.3500	0.310	0.0018
−30 + 20	25	20.0	2.3300	2.00	0.0117
−20 + 10	15	28.0	3.3300	2.86	0.0167
−10 + 5	7.5	37.5	4.4200	68.1	0.3981
−5 + 0	2.5	2.5	0.2900	25.8	0.1510

$$(Q_{std})_1 = 0.676\ Q_1 = (0.676)(31{,}880.0) \simeq 21{,}551 \text{ SDCFM}$$

Therefore,

$$G_{tf_1} = (0.0724)(21{,}551) \simeq 1{,}560 \text{ lbm/min}$$

From Eq. (2),

$$G_{tD_1} = (52.5)(1{,}560) = 81{,}900 \text{ gr/min} \simeq 11.7 \text{ lbm/min}$$

This can also be calculated as follows:

$$G_{tD_1} = 3.80 \left(\frac{21{,}550}{7000 \text{ gr/lbm}}\right) = 11.7 \text{ lbm/min}$$

APPENDIX C
TOTAL PRESSURE DROP — GENERAL TOTAL PRESSURE METHOD

(This Appendix is not part of ASME PTC 21-1991.)

In dealing with energy loss (mechanical energy converted into heat), only kinetic energy is considered. Therefore, ΔP_t should be zero under static conditions. In all the equations in para. 5.2 of PTC 21, it is of no consequence whether the upstream station is number 1 or number 2. When selecting the reference elevation, the proper sign for the direction should be utilized. If the reference elevation is below the test station, Z is positive. If it is above the test station, Z is negative.

Assuming steady state and constant mass flow rate, but with all the other conditions in para. 5.3.1 violated, it can be shown that

$$Z_1 \frac{g}{g_c} + \frac{\overline{V}_1^2}{2g_c} - \int_1^2 \frac{dP_{sa}}{\rho_f} - Z_2 \frac{g}{g_c} - \frac{\overline{V}_2^2}{2g_c} = F - W_e \quad (22)$$

where

F = friction loss, ft-lbf/lbm

W_e = work by external source on the system, ft-lbf/lbm

If ρ_f = constant and $W_e = 0$, then Eq. (11) will result.

Assuming that the system is isothermal, i.e., the flue gas temperature is unchanged, then

$$\int_1^2 \frac{dP}{\rho_f} = -\frac{RT}{M} \ln \frac{\rho_{f1}}{\rho_{f2}} = -\frac{RT}{M} \ln \frac{P_{sa1}}{P_{sa2}} \quad (23)$$

where

R = gas constant = 1546 [(ft-lbf)/(°R-lb-mole)]

T = absolute flue gas temperature (°R = °F + 460)

M = molecular weight of the flue gas, lbm/lb-mole

P_{sa} = absolute flue gas static pressure, lbf/ft^2

Then

$$F = \frac{g}{g_c}(Z_1 - Z_2) + \frac{1}{2g_c}(V_1^2 - V_2^2) + \frac{RT}{M} \ln \frac{P_{sa1}}{P_{sa2}} + W_e \quad (24)$$

NOTES:

(1) A situation where W_e is present occurs when a pump generated water jet in a wet scrubber, after a quencher, adds energy through momentum exchange to the flue gas stream at constant temperature.

(2) Pressure drop is calculated by multiplying F (ft-lbf/lb), as determined by Eq. (24), by the calculated average flue gas density (lbm/ft^3).

EXAMPLE 1

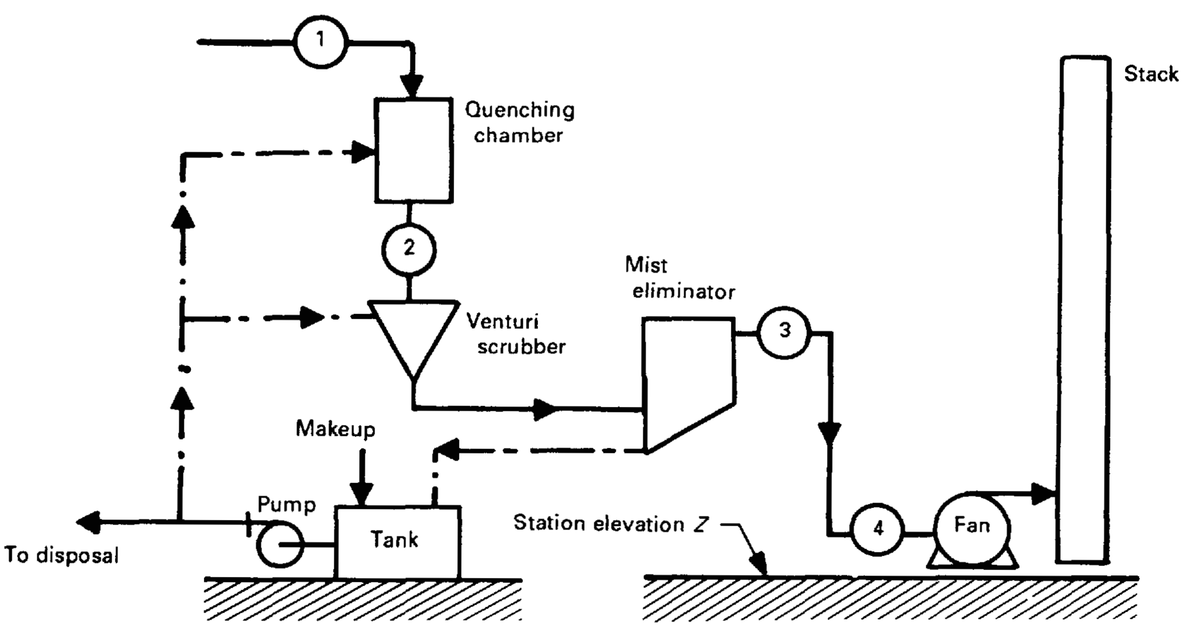
A calculation of the system ΔP_t, i.e., between stations 1 and 4 in Fig. C1, is required. None of the equations given above is applicable, since the mass ratio between stations 4 and 1 is 1.08 > 1.05 (see para. 5.3.1). Therefore, $\Delta \overline{P}_t$ is calculated between stations 2 and 4. The energy required by the fan to overcome the energy losses between stations 1 and 2 can be calculated as stated in para. 5.3.4. However, the specific analysis is not within the scope of PTC 21. Based on the data given in Table C1, a review of the conditions given in para. 5.3.1 indicated that the only items which should be checked are the conditions for the flue gas density and average velocity. For both, the deviation is greater than 5%. Therefore, the last two conditions were not met.

Hence, the General Total Pressure Method in this Appendix should be utilized. However, in order to simplify the calculation, the Total Pressure Method of para. 5.3.3 is utilized, and therefore the average

TABLE C1 TABULATION OF VALUES FOR EXAMPLE 1

Variable	Station 1	Station 2	Station 3	Station 4
Flue gas weight, lbm/min	537.5	582.0	582.0	582.0
Flue gas volume, ft^3/min	25,000	11,323	11,975	11,975
Flue gas temperature, °F	1,200	165	165	165
Flue gas density ρ_f, lbm/ft^3	0.0215	0.0514	0.0486	0.0486
Average velocity $\overline{V}$, ft/sec	60	60	60	50
Measured static pressure P_{sg}, in. WG	−2.0	−4.0	−25.0	−25.5
Elevation Z, ft	60	30	25	5
Barometric pressure P_b, lbf/in.^{2} [Note (1)]	14.0	14.0	14.0	14.0

NOTE:
(1) Barometric pressure P_b may not be constant due to the elevation difference of 55 ft.



GENERAL NOTES:
(a) Sampling stations 1 through 4 are described in Table C1.
(b) The liquid loop is designated — · — · —.
(c) The gas loop is designated ————.

FIG. C1 TOTAL PRESSURE DROP (EXAMPLE)

density is employed (see Example 2 for the effect of this precision). Then

$$\bar{\rho}_t = \frac{0.0514 + 0.0486}{2} = 0.0500 \text{ lbm/ft}^3$$

Using Eq. (13),

$$(P_{sa})_2 = -4 + P_b = -\frac{4}{0.19224} + (14)(144)$$

$$= 1995.19 \text{ lbf/ft}^2$$

$$(P_{sa})_4 = -25.5 + P_b = -\frac{25.5}{0.19224} + (14)(144)$$

$$= 1883.35 \text{ lbf/ft}^2$$

From Eq. (12),

$$\bar{P}_{t_2} = 1995.19 + \left|\frac{1}{(2)(32.174)}\right|(0.0500)(60^2)$$

$$= 1997.99 \text{ lbf/ft}^2$$

$$\bar{P}_{t_4} = 1883.35 + \left|\frac{1}{(2)(32.174)}\right|(0.0500)(50^2)$$

$$= 1885.29 \text{ lbf/ft}^2$$

NOTE: 1/0.19224 is utilized to convert in. WG into lbf/ft^2, and similarly 144 is utilized to convert 14 lbf/in.^2 into lbf/ft^2.

Then from Eq. (11),

$$(\Delta P_t)_{2-4} = 1997.99 - 1885.29 + (0.0500)(30) - (0.05)(5)$$

$$= 113.95 \text{ lbf/ft}^2$$

or

$$(\Delta \bar{P}_t)_{2-4} = (113.95)(0.19224) = 21.91 \text{ in. WG}$$

EXAMPLE 2

We repeat the previous example, except that this time the densities are not averaged. Instead, the method of para. 5.3.4 is utilized. Here

$$W_e = 0$$

$$T = 460 + 165 = 625°\text{R}$$

$$M \simeq 28 \text{ lbm/lb-mole}$$

Using Eq. (24) [note that while numerically $g = g_c$, the units are, of course, different; they are ft/sec^2 for g and (ft-lbm)/(sec^2-lbf) for g_c],

$$F = (30 - 5) + \frac{1}{2(32.174)}(60^2 - 50^2)$$

$$+ \frac{(1546)(625)}{28} \ln \frac{1995.19}{1883.35}$$

$$= 2032.82 \text{ ft-lbf/lbm}$$

$$(\Delta \bar{P}_t)_{2-4} = (F)(\rho_{f_4})(0.19224), \text{ in. WG}$$

$$= (2032.82)(0.0486)(0.19224) = 18.99 \text{ in. WG}$$

Therefore, the averaging of ρ_f in Example 1 generated an error of about 3 in. WG in overestimating the pressure drop which the fan has to overcome.

Note that the pressure drop was calculated after the flue gas was quenched, and therefore the assumption of isothermal process is valid.

APPENDIX D
EXCEEDING STATISTICAL CRITERION — EXAMPLE

(This Appendix is not part of ASME PTC 21-1991.)

The average particulate matter concentration at an inlet of an electrostatic precipitator in a power plant burning coal, with a spray dryer for SO_2 removal, was measured 10 times, i.e., $N = 10$. The results were (in gr/scfm): 14.3, 15.2, 14.6, 14.7, 14.8, 13.4, 14.6, 15.2, 14.5, and 15.0.

From Eq. (14), $P_\theta = 1 - [1/(2)(10)] = 0.95$.

From Table 2, $T = 1.96$.

From Eq. (17), $S = 0.523$.

From Eq. (18), $\overline{X} = 14.63$.

Utilizing Eq. (19) for each of the test results indicates that only for $X = 13.4$,

$$T_{cal} = \frac{13.4 - 14.63}{0.523} = 2.35 > 1.96$$

All other comparison values yield $T_{cal} < 1.96$; therefore, it is clear that the only outlier is for $X = 13.4$.

APPENDIX E
MAXIMUM ERROR — EXAMPLE

(This Appendix is not part of PTC 21-1991.)

Measurement of velocity pressure in a duct, utilizing a pitot tube and a manometer, is analyzed by

$$\overline{P}_V = K_p \frac{1}{2g_c} \overline{\rho}_f \overline{V}^2$$

where

$\overline{P}_V$ = average velocity pressure, lbf/ft²

K_p = pitot tube constant ($K_p = f[V]$)

Assuming that a single point measurement (precalibrated) yields $\overline{P}_V$ for the duct cross section,

$$\overline{V} = \left(\frac{2g_c}{K_p}\right)^{1/2} \left(\frac{\overline{P}_V}{\rho_f}\right)^{1/2}$$

Applying Eq. (20) on V,[1]

$$\Delta V = \left(\frac{2g_c}{K_p}\right)^{1/2} \left| \frac{1}{2} \frac{\overline{P}_V^{-1/2}}{\rho_f^{1/2}} \Delta P_V + \frac{1}{2} (P_V)^{1/2} (\rho_f)^{-3/2} \left|\Delta \rho_f\right| \right|$$

[1]The two terms inside the brackets in the equation for ΔV are added because absolute values are used in Eq. (20).

It was determined that

$\overline{P}_V$ = 0.54 in. WG = 2.81 lbf/ft²

ΔP_{Vf} = ±0.1 in. WG = ±0.52 lbf/ft²

$\overline{\rho}_f$ = 0.055 lbm/ft³ and $\Delta \rho_f$ = $\pm 2.75 \times 10^{-3}$ lbm/ft³

K_p = 1

Then

$$\Delta V_f = \pm [(2)(32.17)]^{1/2} \times \left[\frac{1}{2}\frac{(2.81)^{-1/2}}{(0.055)^{1/2}}(0.52) + \frac{1}{2}\frac{(2.81)^{1/2}}{(0.055)^{3/2}}(2.75 \times 10^{-3})\right]$$

$$= \pm 6.74 \text{ ft/sec}$$

Then for V, where

$$V = \left[\left(\frac{(2)(32.17)}{1}\right)\left(\frac{2.81}{0.055}\right)\right]^{1/2} = 57.33 \text{ ft/sec,}$$

the maximum error is [(6.74)/(57.33)](100) = 11.76%.

APPENDIX F
EFFECT ON EFFICIENCIES OF VARIATIONS IN TEST MEASUREMENTS

(This Appendix is not part of ASME PTC 21-1991.)

Table F1 provides an example from an actual test of a fabric filter on an industrial steam generator rated at 640,000 lb steam/hr with better than average sampling locations and test facilities. Sampling tests conducted in accordance with PTC 38.

TABLE F1 EXAMPLE OF EFFECT ON EFFICIENCIES OF VARIATIONS IN TEST MEASUREMENTS

Item	Inlet Data and Conditions							Outlet Data and Conditions						
		Variation in Test Measurement							Variation in Test Measurement					
	Actual Data	+0.01 in. Stack Velocity	+0.20 in. Orifice	+10°F Stack Temp.	+10.00% Catch	+0.5% Oxygen	+11.76% Higher Gas Flow	Actual Data	+0.01 in. Stack Velocity	+0.02 in. Orifice	+10°F Stack Temp.	+10.00% Catch	+0.5% Oxygen	+11.76% Higher Gas Flow
Results														
Particulate, lb/hr	1552.36	1582.98	1551.58	1543.06	1707.60	1551.87	1734.92	8.54	8.68	8.53	8.48	9.39	8.53	9.54
Percent difference from actual, %	...	1.973	−0.050	−0.599	10.000	−0.031	11.760	...	1.675	−0.051	−0.620	10.000	−0.031	11.760
Collection efficiency, %														
Based on actual outlet data	99.450	99.461	99.450	99.447	99.500	99.450	99.508	...	...	...	...	...	...	...
Based on actual inlet data	...	...	...	...	...	...	...	99.450	99.441	99.450	99.453	99.395	99.450	99.385
Change, %	...	0.011	0.000	−0.003	0.050	0.000	0.058	...	−0.009	0.000	0.003	−0.055	0.000	−0.065
Collection efficiency, %, based on same deviations in both inlet and outlet	99.450	99.452	99.450	99.450	99.450	99.450	99.450	...	...	...	...	...	...	...
Change, %	...	0.002	0.000	0.000	0.000	0.000	0.000	...	...	...	...	...	...	...
Uncertainty Values — Square Root of the Sum of the Squares, %														
Variation inlet — actual outlet	0.078													
Actual inlet — variation outlet	0.086													
Same variation — inlet and outlet	0.002													
Combined inlet lower gas flow and outlet higher gas flow, ±11.76%	0.158													
Test Data and Calculations														
Net time of test, min	80	...	...	...	...	...	...	120	...	...	...	...	...	...
Net sample points	40	...	...	...	...	...	...	40	...	...	...	...	...	...
Sample nozzle diameter, in.	0.311	...	...	...	...	...	...	0.242	...	...	...	...	...	...
Average orifice pressure drop, in. H_2O	1.8	1.8	2.0	1.8	1.8	1.8	1.8	0.86	0.86	1.06	0.86	0.86	0.86	0.86
Volume of dry gas sampled, ft^3, at meter conditions	59.561	...	...	...	...	...	...	63.582	...	...	...	...	...	...
Average gas meter temp., °F	105	...	...	...	...	...	...	103	...	...	...	...	...	...
Volume of dry gas sampled, at standard conditions, SCF	54.119	54.119	54.147	54.119	54.119	54.119	54.119	56.335	56.335	56.364	56.335	56.335	56.335	56.335
Total H_2O collected in impingers and silica gel, ml	94.5	...	...	...	...	...	...	102	...	...	...	...	...	...
Volume of water vapor at standard conditions, SCF	4.45	...	...	...	...	...	...	4.80	...	...	...	...	...	...
Moisture by volume, %	7.6	...	...	...	...	...	...	7.9	...	...	...	...	...	...
Mol. fraction dry gas	0.924	0.924	0.924	0.924	0.924	0.924	0.924	0.921	0.921	0.921	0.921	0.921	0.921	0.921
CO_2, % by volume dry	13.1	...	...	...	...	...	...	13.1	...	...	...	...	...	...
O_2, % by volume dry	5.5	5.5	5.5	5.5	5.5	6.0	5.5	5.5	5.5	5.5	5.5	5.5	6.0	5.5
CO, % by volume dry	0	...	...	...	...	...	...	0	...	...	...	...	...	...
N_2, % by volume dry	81.4	81.4	81.4	81.4	81.4	80.9	81.4	81.4	81.4	81.4	81.4	81.4	80.9	81.4

TABLE F1 EXAMPLE OF EFFECT ON EFFICIENCIES OF VARIATIONS IN TEST MEASUREMENTS (CONT'D)

Item	Inlet Data and Conditions							Outlet Data and Conditions						
		Variation in Test Measurement							Variation in Test Measurement					
	Actual Data	+0.01 in. Stack Velocity	+0.20 in. Orifice	+10°F Stack Temp.	+10.00% Catch	+0.5% Oxygen	+11.76% Higher Gas Flow	Actual Data	+0.01 in. Stack Velocity	+0.02 in. Orifice	+10°F Stack Temp.	+10.00% Catch	+0.5% Oxygen	+11.76% Higher Gas Flow
Test Data and Calculations (Cont'd)														
Molecular weight — dry stack	30.32	30.32	30.32	30.32	30.32	30.34	30.32	30.32	30.32	30.32	30.32	30.32	30.34	30.32
Molecular weight — stack	29.38	29 38	29.38	29.38	29.38	29.40	29.38	29.35	29.35	29.35	29.35	29.35	29.37	29.35
Static pressure of stack gas, in. H_2O	−2.0	..	...	...	...	...	...	−0.8	...	...	...	...	...	...
Stack pressure, abs., in. Hg	28.85	...	...	...	...	...	...	28.94	...	...	...	...	...	...
Average stack temp., °F	367	367	367	377	367	367	367	339	339	339	349	339	339	339
Average velocity head of stack gas, in. H_2O	0.251	0.261	0.251	0.251	0.251	0.251	0.251	0.296	0.306	0.296	0.296	0.296	0.296	0.296
Average stack gas velocity, FPS	35.5	36.2	35.5	35.8	35.5	35.5	39.7	37.9	38.5	37.9	38.1	37.9	37.9	42.4
Stack flow rate, dry standard CFM	101847	103856	101847	101236	101847	101815	113824	116570	118523	116570	115847	116570	116533	130279
Stack flow rate, dry actual CFM	179107	182640	179107	180186	179107	179050	200169	197996	201312	197996	199231	197996	197934	221280
Percent isokinetic	70.4	69.1	70.5	70.8	70.4	70.4	63.0	109.7	107.8	109.7	110.3	109.7	109.7	98.1
Particulate, mg	6238.1	6238.1	6238.1	6238.1	6861.91	6238.1	6238.1	31.2	31.2	31.2	31.2	34.32	31.2	31.2
Particulate, gr/DSCF	1.7785	1.7785	1.7776	1.7785	1.9564	1.7785	1.7785	0.0085	0.0085	0.0085	0.0085	0.0094	0.0085	0.0085
Constants														
Pitot tube coefficient	0.84	...	...	...	...	...	...	0.84	...	...	...	...	...	...
Dry gas meter calibration factor	0.999	...	...	...	...	...	...	0.999	...	...	...	...	...	...
Barometric pressure	29.00	..	...	...	...	...	...	29.00	..	...	...	...	...	...
Stack area, in.^{2}	12,096	...	...	...	...	...	...	12,096	...	...	...	...	...	...

GENERAL NOTE: Boxed values are those that were modified for purposes of illustration.

COMPLETE LISTING OF ASME PERFORMANCE TEST CODES

PERFORMANCE TEST CODES

A complete list of all Performance Test Codes appears at the end of this book.

While providing for exhaustive tests, these Codes are so drawn that selected parts may be used for tests of limited scope.

This document is printed on 50% recycled paper.

50% RECOVERED PAPER MATERIAL means paper waste generated after the completion of the papermaking process, such as postconsumer materials, text books, envelopes, bindery waste, printing waste, cutting and converting waste, butt rolls, obsolete inventories, and rejected unused stock.

D02191

ISBN #0-7918-2129-3