AN AMERICAN NATIONAL STANDARD

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PTC 38 - 1980

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Determining the Concentration of Particulate Matter in a Gas Stream

PERFORMANCE

TEST

CODES

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

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FOREWORD

The first of the ASME Power Test Codes related to the abatement of atmospheric pollution was published in 1941 – PTC 21, "Dust-Separating Apparatus." That Code has served for many years as a basic guide for evaluating the performance of apparatus designed for the removal of particulate matter from combustion process flue gases. Experience with that Code identified a difficult measuring problem, a procedure for measuring the concentration of particulate matter in a gas stream. As recognized by those who have had experience with measurements of this type, this involves many practical difficulties. In an effort to alleviate many of these difficulties, the ASME published a Test Code concerned with this subject in 1957 – PTC 27, "Determining Dust Concentration in a Gas Stream." That Code, along with the earlier Code, has served until very recently as the accepted basic guide for both the performance evaluation of particulate removal apparatus and the determination of particulate matter in stack gas emissions for the control of air pollution and the assurance of compliance with applicable governmental emission control regulations.

However, over the years, with the changes in particulate removal technology, such as the great increase in the physical size of much of the apparatus and the gas flows involved, along with the increasing interest in very small particles and the need for accurately measuring much lower particulate matter concentrations, it became apparent that both PTC 21 and PTC 27 were not fully adequate for all the purposes to which they were being applied. Realizing that the various physical and chemical properties of the particulate matter involved were usually a major factor in the performance of the apparatus designed and installed for its removal, the ASME published a Code on this subject in 1965 – PTC 28, "Determining the Properties of Fine Particulate Matter." That Code has become the accepted guide for characterizing the properties of the particulate matter for meeting most of the needs in this area of concern.

With the increasing public concern in the early 1970's for environmental improvement, and in particular air pollution control, new problems became apparent. Many regulatory agencies in all levels of government either issued their own new test procedures for the measurement of particulate matter in stack gases or adopted various test procedures developed by other organizations and often mandated their use for regulatory purposes. Many of these test procedures were later found to be unsuitable, both as to the practicability of their use in the field and the validity of the test data which they produced. A major source of uncertainty in most of these test procedures was the fact that, in addition to measuring the particulate matter actually present in the gas stream, the test apparatus involved also converted certain gaseous components of the gas stream to substances which were collected, measured, and reported as "particulate matter." This situation led to serious problems in the establishment of valid criteria for evaluating the performance of emission control apparatus for operational, commercial, and regulatory purposes.

In an effort to eliminate as many of these problems as possible, ASME Performance Test Code Committee 38 was organized in 1972 and given the task of developing test codes for the measurement of fine particulate matter which would employ the best practical techniques of currently known technology to meet the increasingly stringent requirements of those air pollution abatement activities concerned with the control of particulate emissions resulting from combustion processes.

This Test Code is the result of several years of intensive effort by that Committee, with the cooperation and assistance of other organizations, to evaluate the problems involved and the technology available for accurately determining the concentration of particulate matter in a gas stream by practicable means. Complete solutions to all problems involved in this complex field of testing cannot be provided in a generalized Code. However, this Code is believed to be the best compendium of data and guidelines available for this purpose and it covers the vast majority of cases encountered. If properly used, it will provide the most valid test results possible.

PTC 38 on Determining the Concentration of Particulate Matter supersedes PTC 27 on Determining Dust Concentration in a Gas Stream and should be used in conjunction with the revised PTC 21 on Dust Separating Apparatus.

This Code was approved by the Performance Test Codes Supervisory Committee on March 20, 1980. It was approved by ANSI as an American National Standard on May 15, 1980.

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AN AMERICAN NATIONAL STANDARD

ASME PERFORMANCE TEST CODE

Code for
DETERMINING THE CONCENTRATION OF PARTICULATE MATTER IN A GAS STREAM

SECTION 0 – INTRODUCTION

0.1 This Code sets forth recommended procedures and devices for the measurement of particulate matter suspended in gases flowing in a duct or stack. While this Code is oriented toward gases resulting from combustion processes, its use for other gas streams is not precluded if test parameters are compatible with those discussed here in.

0.2 *To obtain valid test results it is absolutely necessary that there is a full understanding of the problems involved in each test situation and that every effort is made to select and properly employ the appropriate procedures and apparatus for each case. Therefore, it is mandatory that this Code be studied in its entirety, with particular attention being given to the Appendix, Section 8, before planning any test program.*

0.3 As this Code describes various options in respect to test apparatus and methodology which is appropriate to various test situations, the choice between suitable options must be made both on the basis of the nature of the test and the regulatory and/or contractual restrictions which may be a part of the requirements for conducting the tests.

Therefore, when the use of this Code is specified in commercial agreements regarding system performance evaluation or in source emission control regulations, either the appropriate approved options should be clearly defined or the mechanism stated for establishing the approved option(s) appropriate to the particular test situation.

0.4 Unless otherwise specified, all references to other Codes refer to ASME Performance Test Codes.

0.5 Any test to determine the particulate matter concentration in a gas stream should comply with the Code on General Instructions. In particular, the test objectives shall be agreed upon by the interested parties before the test is performed.

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 Section 4 of this Code on Instruments and Methods of Measurement describes instruments and methods which are likely to be required and discusses their application, calibration, sensitivity, accuracy, etc. Performance Test Code 19, Supplements on Instruments and Apparatus, referred to in this Code are designated by the abbreviation, I & A.

SECTION 1 – OBJECT AND SCOPE

1.1 OBJECT OF TEST

The Test object is to determine the weight rate of flow of particulate matter carried in a gas stream confined in a duct or stack. The test object is accomplished by (a) measurement of average weight concentrations of particulate matter in the gas stream, and (b) determination of total gas flow rate.

Data thus obtained may be utilized for such purposes as the performance evaluation of gas cleaning apparatus/systems, compliance testing in conjunction with emission control and performance regulations promulgated by regulatory agencies, etc.

1.2 SCOPE OF TEST

1.21 Concentration of Particulate Matter

This Code prescribes methods for measuring the average weight concentration of particulate matter carried in a gas stream. Measurement on any other basis (e.g., particle count, dust spot, opacity, etc.) is beyond the scope of this Code.

1.22 Gas Flow Measurement

Determination of total gas flow may be based on measurement of velocity pressure and gas density at representative points in the duct cross section, on actual combustion calculations (stoichiometry), or by data from calibrated gas metering devices. Alternate methods for measuring total gas flow rate may be used by agreement of all the concerned parties.

1.23 Particle Size Measurement

The scope of this Code does not include the measurement of particle size distribution. Test procedures for this purpose are contained in ASME Performance Test Code 28. While some in situ type samplers designed for the collection of particulate matter in various size fractions may have a limited capability for determining total particulate matter concentrations in a gas sample, data thus obtained should only be used for the measurement of particle size distribution and not for the weight rate of flow of particulate matter in the gas stream.

SECTION 2 – DESCRIPTION AND DEFINITIONS OF TERMS

2.1 This Code specifies the test procedures to be employed in the determination of the concentration of particulate matter in a gas stream and the total flow rate of the gas. The terms used in connection with the test procedures are defined by the following:

2.2 PARTICULATE MATTER

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 and pressure 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.

2.21 This definition is intended to exclude from consideration those substances which may be formed outside the stack or duct or in a sampling train on cooling the gas stream to a lower temperature than prevails in the channeled gas.

2.22 The measurement of particulate matter which may form in the outside atmosphere requires techniques which are outside the scope of this Code.

2.3 TEST AND RUN

2.31 A "Test," as applied in this Code, means the entire investigation.

2.32 A "Run" is a subdivision of a "Test" consisting of a complete set of observations and recorded data taken at regular intervals for a period of time during which sampling of the gas stream was conducted.

2.4 NOMENCLATURE AND UNITS OF MEASUREMENT

2.41 The nature of this Code is such that it will often find application in conjunction with existing technical specifications, commercial agreements, and governmental regulations. The terminology and the units of measurement contained therein may range from those considered to be the "accepted standards" for the intended purposes of such documents at the time they were written prior to the promulgation of this Code to those based upon the SI System which may be written subsequent to the promulgation of this Code.

2.42 It is preferred, in accordance with ASME policy, that the SI System for units of measurements be utilized whenever practicable in the application of this Code. However, it is realized that, at the time immediately following its promulgation, its major applications will be in conjunction with specifications, agreements, and regulations utilizing the previously acceptable nomenclature and units of measurement. Therefore, to make this Code readily applicable to present and future situations, the formulae, tables and graphs and calculation of results are stated herein in accordance with presently existing good engineering practices – with provisions being made for the conversion of the Code to the SI System by the inclusion of the definitions of pertinent SI units of measurement, conversion factors from other units of measurement, and general guidance in respect to the utilization of the SI System.

2.43 While a major effort has been made to standardize the nomenclature and the related symbols used throughout the Code, the unique nature of certain calculations involved requires that special symbol notations be employed in these calculations to avoid confusion. Hence, both a general system of nomenclature and related symbolic notation is presented in this Section and, for the special cases where those are inadequate or inappropriate for special purposes, specialized tables of nomenclature are provided where applicable in this Code.

2.44 The use of the SI Units with this Code is based upon ASME Guide SI-1, "Orientation Guide for SI (Metric) Units," Eighth Edition (Reference [11] in Section 7). Excerpts from this publication are printed in Appendix L of the Code to provide readily available guidance with re-

Table 2-1 TABLE OF TERMS

Term	Symbol	Description	Conventional Units: Units	Conventional Units: Name of Unit	SI Units: Units	SI Units: Name of Unit	Conversion Factors: Conventional to SI
Length	*L*	Dimension or Distance	in.	inch	m	meter	2.540 E−02
			ft	foot	m	meter	3.048 E−01
			mm	millimeter	m	meter	1.000 E−03
			cm	centimeter	m	meter	1.000 E−02
Mass	Wt	Weight of material	lb	pound mass (avoir)	kg	kilogram	4.536 E−01
			ton	ton	kg	kilogram	9.072 E+02
			gr	grain (avoir)	kg	kilogram	6.480 E−05
			gm	gram	kg	kilogram	1.000 E−03
Time	*t*	Duration of time	sec	second	s	second	1.000 E+00
			min	minute	s	second	6.000 E+01
			hr	hour	s	second	3.6 E+03
Gravitational Constant	*g*	Gravitational Constant	g	gravitational constant			
			ft/sec^2	32.17 ft/sec^2	m/s^2	meters per $second^2$	9807 E+00
			cm/sec^2	980 cm/sec^2	m/s^2	meters per $second^2$	9807 E+00
Force	*F*	Force	lb	pound force	N	Newton, $(kg \cdot m/s^2)$	4.448 E+00
			pdl	poundal	N	Newton, $(kg \cdot m/s^2)$	1.383 E−01
			kgf	kilogram force	N	Newton, $(kg \cdot m/s^2)$	9.807 E+00
			dyne	dyne	N	Newton, $(kg \cdot m/s^2)$	1.000 E−02
Area	*A*	Cross-sectional area	$in.^2$	square inches	m^2	square meters	6.452 E−04
			ft^2	square feet	m^2	square meters	9.290 E−02
			cm^2	square centimeters	m^2	square meters	1.000 E−04
Volume	Vol	Volume, space or material	ft^3	cubic feet	m^3	cubic meters	2.832 E−02
			gal	gallons (U.S.)	m^3	cubic meters	3.785 E−03
			l	liter	m^3	cubic meters	1.000 E−03
			ml	milliliter	m^3	cubic meters	1.000 E−06
Particle Size	*D*	Diameter of particle	μm	micron or micrometer	m	meter	1.000 E−06
Velocity	*V*	Velocity, object or material	ft/sec	feet per second	m/s	meters per second	3.048 E−01
			in./sec	inches per second	m/s	meters per second	2.540 E−02
			cm/sec	centimeters per second	m/s	meters per second	1.000 E−02
Flowrate, volumetric	*Q*	Volumetric flowrate	CFM	cubic feet per minute	m^3/s	cubic meters per second	4.720 E−04
			GPM	gallons per minute	m^3/s	cubic meters per second	6.308 E−05
Flowrate, mass	*G*	Mass flowrate	lb/hr	pounds per hour	kg/s	kilograms per second	1.260 E−04
			lb/min	pounds per minute	kg/s	kilograms per second	7.560 E−03
Temperature	*T*	Temperature, object or material	°F	degrees Fahrenheit	°C	degreees Celsius	°F − 32/1.8
			°R	degrees Rankine	°C	degrees Celsius	°R/1.8
			°C	degrees Centigrade	°C	degrees Celsius	1.000
			°K	degrees Kelvin	°C	degrees Celsius	°K − 273.15

Table 2-1 TABLE OF TERMS (Cont'd)

Term	Symbol	Description	Conventional Units		SI Units		Conversion Factors	
			Units	Name of Unit	Units	Name of Unit	Conventional to SI	
Temperature Interval	ΔT	Temperature difference	°F	degrees Fahrenheit	°C	degrees Celsius	5.556	E−01
			°C	degrees Centigrade	°C	degrees Celsius	1.000	E−00
Pressure	P	Pressure, gas or liquid	lb/in.^{2}	pounds per square inch	Pa	Pascals, (N/m^2)	6.895	E+03
			in. H_2O	inches water gage	Pa	Pascals, (N/m^2)	2.491	E+02
			in. Hg	inches Hg manometer	Pa	Pascals, (N/m^2)	3.387	E+03
			mm Hg	millimeters Hg manometer	Pa	Pascals, (N/m^2)	1.333	E+02
			Atm	Atmospheres	Pa	Pascals, (N/m^2)	1.014	E+05
			bar	bars	Pa	Pascals, (N/m^2)	1.000	E+05
Density	ρ	Density of material	lb/ft^3	pounds per cubic foot	kg/m^3	kilograms per cubic meter	1.602	E+01
			lb/gal	pounds per gallon	kg/m^3	kilograms per cubic meter	1.198	E+02
			gm/cm^3	grams per cubic centimeter	kg/m^3	kilograms per cubic meter	1.000	E−03
Viscosity	η	Viscosity, gas or liquid	poise	poise	P	poise, (0.1 Pa • s)	1.000	E+00
Concentration	Conc	Weight of material in volume of gas or liquid	lb/ft^3	pounds per cubic foot	kg/m^3	kilograms per cubic meter	1.602	E+01
			lb/gal	pounds per gallon	kg/m^3	kilograms per cubic meter	1.198	E+02
			gm/cm^3	milligrams per cubic meter	kg/m^3	kilograms per cbuic meter	1.000	E−06
Energy, thermal	HV	Heating value of fuel	Btu	British Thermal Unit	J, or N • m	Joule or Newton meter	1.055	E+03
			Cal.	calorie	J, or N • m	Joule or Newton meter	4.186	E+00
Energy, electrical	KWH	Electrical energy	kWhr	kilowatt hour	J, or N • m	Joule or Newton meter	3.600	E+06
Electrical Power	W	Electrical power	W	watt	W, or J/s	Watts or Joules per second	1.000	E+00

spect to the basic system of units and their use. A thorough understanding of all the material contained in ASME Guide SI-1 is essential to the proper use of the SI System.

2.45 To maximize the usefulness and applicability of test results in the future, it is recommended that all test results be reported, whenever possible, in SI Units as well as in the system of units originally deemed applicable for the specific test(s) involved.

2.5 TABLE OF TERMS

2.51 Table 2-1 contains a listing of the terminology and nomenclature used generally throughout the Code. Conversion factors are provided for conversion of the stated units of measurement to the SI System of Units.

2.52 Where the need for different systems of nomenclature exists within the Code to define unique test parameters, the required nomenclature is listed in Tables accompanying the calculation procedures involved. Provisions have been made for conversion of the units used to the SI System.

This Table contains a listing of the terms commonly used in the measurement of the concentration of particulate matter in a gas stream. The units of measurement given are those in general use at the time this Code was written. The appropriate SI units of measurements, to be substituted for the given units, are also given along with conversion factors for converting from the conventional units to the SI units of measurement.

In actual practice, these terms are usually used with subscripts in formulae, graphs, and calculations to indicate their sepcific meaning for particular usage situations. The nature of the subscripts may vary greatly, depending on the source of the publication and the nature of the measurements involved. Hence, no standardized system for subscripts is included in this Code. Whenever subscripts are used, however, their meanings should be clearly indicated.

Note 1: The column of Conversion Factors contains, on the left, the numerical value to be used in exponential notation and, on the right, the exponent for a base of 10. For example: 2.540 E – 02 signifies that the factor is 2.540×10^{-2} or 0.0254.

Note 2: While it is realized that the term "mass" is more strictly correct than the term "weight" when reforming to such units of measurement as pounds mass, kilograms, grains, etc., the more commonly used term "weight" is used frequently in this Code to avoid confusion for those using it who are much more familir with the generally used term for this parameter. This does not preclude the desirable practice of using the term "mass" vice "weight" whenever practicable and understandable.

SECTION 3 – GUIDING PRINCIPLES

3.1 ITEMS OF AGREEMENT

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

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

(a) The object or objects of the test (see paragraph 1.1).

(b) Date and time of the test.

(c) The number, type, and location of sample trains and other instruments where alternates are permitted (see paragraphs 3.51 and 3.53) and the test procedures to be employed in their use.

(d) Number and location of all sampling points.

(e) Method of determining and maintaining constancy of process conditions during the test (see paragraph 3.54).

(f) Gas flow rates in the duct(s) or stack to be tested.

(g) Method of determining total gas flow; whether by combustion calculations, by process calculations, or by velocity head measurements (see paragraph 3.52).

(h) Number and duration of runs (see paragraph 3.55).

(i) Duration of steady state operation before sampling is commenced (see paragraph 3.54) and, in the case of new or modified installations, the minimal "shakedown" operational period required prior to testing.

(j) Designation of the procedures for making calibrations, weighings, and other appropriate measurements, and selection of the laboratories for carrying out various test procedures.

(k) Maximum deviations of test measurements and conditions between replicate runs that will be acceptable, and the requirements for additional runs where their deviations are exceeded.

3.12 During actual site testing, the method of determining the particulate matter concentration of gases must be adapted to the conditions of constructions and operation encountered in each particular case. Unfortunately, ideal conditions are seldom found in field testing. Therefore, the parties to the test should investigate the field conditions thoroughly before making arrangements for conducting a test.

3.2 TOLERANCES

This Code specified the desired conditions and procedures for obtaining valid and accurate test results but the definition of uncertainties in respect to overall test accuracy and repeatability is not within its scope.

Ideal test conditions may be unobtainable in many test situations. This Code provides guidance for dealing with such non-ideal conditions so as to maximize the accuracy of the test results. Provisions to allow for uncertainties in measurements, resulting from 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.

3.3 WITNESSES TO A TEST

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

3.32 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.

3.4 PRELIMINARY RUNS

One or more preliminary runs may be conducted for such purposes as checking instruments and procedures and/or making minor adjustments, the need for which was not evident during the preparations for the test. Any preliminary run, when completed, may be declared, by mutual agreement, to be an official run.

3.5 TEST PROCEDURES–GENERAL PRINCIPLES

The major points in connection with the test (see paragraph 3.11) having been agreed upon, it is then necessary to prepare the detailed procedure for the test.

In planning the test, attention should be accorded to the problem of obtaining a truly representative sample over the total cross section of the duct in view of the tendency of particles to stratify due to distortions of gas flow. This problem is related to (a) the selection of a most favorable sampling location, (b) the number and pattern of sampling points in the cross section, (c) the frequency of readings, and (d) the number and duration of runs. See Appendix H.

The function of the sampling device is essentially that of withdrawing a portion of the particulate matter laden gas at such a rate and in such a manner that it represents a true sample of filterable material at the point of extraction. There can be a variety of designs that satisfy these requirements by means of isokinetic sampling.

It is strongly recommended that prior to the test run all pertinent information required for translating velocity head readings into isokinetic sampling rates be put in readily calculable form, preferably as easily read charts, so that flue velocities read as a pretest procedure or read concurrently with the testing, can be immediately translated during the actual sampling run into isokinetic rates. Suggested procedures for doing this are given in Appendix J.

3.51 Sampling Location

Selection of Sampling Cross Section

Care must be taken to select the best possible sampling cross section of the duct. A straight run of duct preceding the point of measurement is, of course, preferable. In any event, avoid locations near sudden changes in area of direction. Such changes may cause fluctuating particulate matter stratification, or extreme turbulence leading to skewed or reversed gas flow. The use of vertical ducts, where possible is preferable as this eliminates the problems of settled particulate matter in the duct. In either horizontal or vertical ducts, the preferred location is at least 8 diameters downstream and 2 diameters upstream from any flow disturbulence. Such a sampling point location is often not available. Hence, in either horizontal or vertical ducts, the location of the test ports related to the number of duct diameters from any flow disturbance will determine the number of sampling positions necessary to obtain valid test results. See Fig. 1 of Appendix H.

The term "equivalent diameter" relates to the cross-sectional area of a rectangular duct which produces the same Reynolds number to the diameter of an equivalent cross-sectional area circular duct and is expressed and calculated as follows:

$$D = 4 \times \frac{\text{Area}}{\text{Perimeter}} = 2 \times \frac{(H \times W)}{(H + W)} \quad \text{where}$$

D = equivalent diameter
H = height of flue or duct
W = width of flue or duct

Access and Service Facilities

Room for test setup and for free movement of the test apparatus during the test should be considered when selecting the sampling location. Staging for personnel and apparatus at the test location and access thereto shall conform to recognized safety codes. Adequacy of lighting, electric power outlets, communication facilities, etc., should also be considered.

Settled Particulate Matter

Particulate matter buildup on the bottoms of horizontal ducts is often encountered and must be considered when establishing duct dimensions for velocity traverses and when sectionalizing the duct into sampling areas. A bottom profile formed under equilibrium flow conditions can be established with sufficient accuracy by probing. This probing should be done at sufficient frequency to identify any changes in the profile during the test. The profile of dust buildup must be shown on a cross-sectional view of the duct if credit is to be obtained for the reduced cross-sectional area.

Bottom particulate matter buildup not only affects gas flow rate determination but often upsets particulate matter concentration determinations because of particulate flow along the bottom of the duct. It is therefore extremely important that the sampling probe be kept well above the buildup. The distance from the top surface of the buildup to the sampler nozzle should be one-half the distance between test zones. For example, if there is a 3 ft distance between test positions in the vertical direction, then the nozzle should be approximately 1½ ft above the surface of the buildup.

Low Velocity Streams

One may encounter duct arrangements where it is impossible to make satisfactory measurements of velocity at the location required for particulate matter sampling because they are too low to be read by any of the recommended instruments. In these circumstances some unconventional procedures may be necessary (see Appendix E).

3.52 Flow Measurement

The determination of a gas mass or volume for the purpose of establishing the rate of flow through a collection device, as it affects collection performance, should utilize the most accurate method available. A full understanding of the accuracy of velocity head measurements which can be made to determine total gas flow should determine whether these flow rates for each test situation should be established by calculation from fuel analysis and flue gas composition or from measurements of velocity head. In many cases, due to less-than-ideal conditions for velocity head measurement, flow determinations from combustion calculations have been found to be more accurate and this method is preferred where applicable. In such cases the flow rates as determined by velocity head measurements are usually higher than those determined by combustion calculations.

Calculation procedure for gas mass per unit weight of fuel is given in PTC 4.1 – "Steam Generating Units," paragraph 7.3.2.02. Gas flow rate will require a knowledge of fuel rate from a fuel metering device, or, in the case of a steam generator, the fuel rate can be established from a measured steam or water flow and a known or calculated steam generator efficiency under test conditions. The accuracy of gas flow rate established by this method will be the accuracy of measurement of gas weight per unit weight of fuel (PTC 4.1, "Probable Measurement Errors," paragraph 3.03.5) and the accuracy of metering devices.

3.53 Number and Distribution of Sample Points

Whether the flue or stack is circular or rectangular in cross section, sampling connections and traverse points should be selected to permit sampling in zones of equal area as illustrated in Appendix H. Since the arrangement of flues and stacks do not always lend themselves to permit locating connections in a preferred relationship to turns and cross-sectional changes, the frequency of traverse points and size of sampling areas will change depending upon this relationship.

Appendix H provides guidance for determining the number and location of sampling areas required for various sampling situations. All data relative to the selection of sampling points and dimensioned drawings of both the sampling cross-sectional profile and the duct arrangement (showing sources of flow disturbance) shall be included in the test report.

Adherence to these guidelines is recommended for accurate, consistent sampling of particulate matter. Since a greater number of points will not impair the sampling accuracy, a greater number of points may be used if desired.

If many sampling points are involved, it may prove advantageous to operate more than one sampler at a time. This can also prove helpful if information is desired, for example, on several ducts serving a common gas cleaning device as a measure of flow distribution between ducts.

3.54 Constancy of Test Conditions

Steady state operating conditions should be established before the start of each run, especially those conditions which affect gas temperature and flow rate. The Pitot tube traverse or actual sampling should not be started until conditions have become steady and remain steady for at least ½ hr. Longer waiting periods may be required to ensure equilibrium conditions when major changes in operation are made. Although constant operating conditions are necessary to obtain the most reliable results, it is recognized that constant operating conditions sometimes cannot be maintained. Variations in flow rate are best understood by those familiar with the process, and the degree of variations acceptable should be established by mutual consent. Flow variations are shown by variations in fan power requirements, fan control settings, gas analyses, fuel input rate, or combinations of these parameters. They can also be determined by continuously monitoring the gas velocity at a single sample point or at individual sampling points during a run.

If possible, during the testing period, all process equipment settings, fan settings, etc., should remain unchanged to assure the consistency of test results. Process recording charts should be included in the test report, if possible, with times of traverse and sampling clearly shown. Checks should be made after the tests on the profiles of settled particulate matter and on equipment settings to determine that they remained essentially unchanged to assure that a valid test has been obtained. When soot blowing or other periodic process action is a part of normal operations, the procedure for including such action, if desired, into the test program should be considered and full agreement obtained from all parties as to how this will be done.

3.55 Duration of Runs

In general, sampling times at each point should be equal increments of the total time. The total sampling time will be that necessary to insure collection of a weighable sample. Calculations should be made for each installation to determine the sampling time necessary to obtain a sample weighable within the accuracy desired. It has been demonstrated that an accurate, weighable catch can usually be obtained during a 1 to 4 hr run at the discharge of high efficiency collection systems.

On certain cyclic operations it is impossible to maintain desired test conditions for an extended duration of run, and in such cases the maximum sampling time will be limited by the cycle time. A complete traverse of points should be made so that the total of the equal time increments for all traverse points should equal the cycle time. Depending upon the length of the cycle, more than three runs may be required to obtain consistent results. Some cases may require the simultaneous use of two or more sampling systems.

3.56 Frequency of Readings

Where the Pitot tube, or velocity head measuring device is an integral part of the sampler, velocity head readings shall be monitored continuously and the sample flow rate, as determined by flowrater, rotameter, or orifice meter, shall be maintained at the proper isokinetic sampling rate to match the velocity head reading.

It is advisable to take Pitot tube traverses prior to sampling to determine the flow pattern and make the proper selection of sample nozzle sizes to obtain isokinetic sample flow rates. When test runs are long in duration, it is desirable to conduct at least a partial traverse again after the sampling period to verify that flow rates and flow patterns have not changed. If, during the sampling period, there is any indication by any process or test instrumentation that operating conditions may be changing, a traverse should be made to determine if changes have occurred.

If the sampling flow is determined by a volume meter, the flow rate can be established immediately after the start of sampling by dividing the meter reading by the corresponding increment of the total sampling time. However, even if an integrating meter is used, it is easier to establish the flow rate by using a flowrater or rotameter in series with the meter.

A record should be kept of flow rates, integrated flow measurements, gas pressures and temperatures at the sampling flow measuring device, at 5 min intervals, or at intervals consistent with the sampling time at each point, together with an indentification of the sampling point location (e.g., at start and finish of each sampling interval when these intervals are longer than 5 min but shorter than 10 min).

Where the sampler is equipped with an integral velocity head measuring device, it is essential to record the velocity head and temperature readings in the duct. This information is necessary to calculate the gas flow by velocity head measurements and can be useful if a check is desired on a calculated combustion gas flow rate.

If sample gas volumes are obtained by the use of a volume meter, the integrator should be read at the exact time of the start and finish of sampling at each sampling point. It is advisable to obtain readings at regular intervals during the run as a check against the total, and as insurance against unforseen interruption or termination of the test run.

3.57 Procedure for Operating Samplers

There are certain general considerations inherent in the use of any sampling device that should be observed to permit obtaining accurate, repeatable results. Specific procedures for different types of sampling devices should be recognized, understood, and followed.

Prior to the start of any run, the preweighed filter and entire sampling system should be inspected and tested to be sure all connections in the sampling system and in the manometer or gage connections are free of leakage. This is particularly important where connections are interposed between the filter medium and the sample gas metering device since, obviously, any leaks ahead of the metering device will cause erroneously high sample gas flow measurements and give a false isokinetic indication (see paragraph 4.51). All apparatus used should be electrically grounded to the ductwork or other good ground.

The sampler probe should be clearly marked to indicate the direction of the sampler nozzle and to permit the operator to recognize when the probe is at the predetermined sampling points.

The equipment being tested should have been at test conditions for an agreed-upon time before starting a run. All parties involved should be aware that a test is proceeding and not alter operating conditions that will affect the conduct of the test. Should any unavoidable changes occur, the testing parties should be advised promptly so the run can be interrupted until test conditions are restored. Some changes may require starting a new test with new filters and clean equipment.

The plugs or caps closing the test ports should be removed and the connections thoroughly cleaned of any loose or adhering deposit that may have accumulated. Be sure that any protective covering over the sampler nozzle is removed. The sampling system should be sealed to prevent any reverse flow during insertion of the probe. This is done by closing the valve or clamping shut the hose to the exhausting system. Where high pressure or drafts exists in a flue or duct at the sampling location, high flow velocities will occur through the open sampling connection, having an aspirating affect which can remove collected particulate matter from the sampling system as the sampling nozzle passes through. Extreme care will be required during this period.

Where the design of the sampling apparatus permits, insert the sampler through the first sampling port with the nozzle facing downstream and allow the sampler to come to operating temperature. After the warm-up time, timing should be started simultaneously with facing the nozzle upstream and establishing isokinetic flow rate.

This sequence of actions should be performed as rapidly as possible. As soon as sampling conditions are stable, temperatures, pressures, and velocity head readings should be recorded and recording continued at 5 min intervals or at intervals consistent with the sampling time at each point. It is recommended that the first sample point be the point of greatest insertion to permit quick warming of the total sample probe and to facilitate probe removal after the completion of sampling through each sample port.

At the appropriate time interval, the sampler should be moved to the next sample point established for this connection and the sampling rate adjusted for isokinetic rate. Readings of temperature, pressure, and velocity heads should continue at equal time intervals. The time interval at each sampling point should be recorded, with the appropriate readings, on the sampling data sheet.

When the last sampling point at a particular test port is completed, timing should be stopped, the sampling flow rate control valve closed, and simultaneously the sample nozzle turned 180 degrees where possible, and the probe removed. The exhausting system may be shut off during the sampler removal from the test port to seal the system and prevent loss of collected sample, However, this is not recommended when the static pressure in the duct is negative.

The procedure should be continued until all sample points have been traversed. This will constitute a test run.

After removal of the sampler from the final point, and after obtaining a final reading of sample gas volume, manipulate the apparatus to recover quantitatively any loose sample in the nozzle ahead of the filter medium.

Extreme care should be exercised to avoid contamination by extraneous material.

After the sampler has cooled sufficiently to handle, it is recommended that the entire sampler head or filter holder and probes exposed to the sample flow, properly encased or plugged, be transported to the laboratory or other clean working area for sample recovery (see paragraph 4.5).

Sufficient replicate runs should be made to comply with the pretest agreement on the number of, and agreement between, runs. An alternate procedure, having special advantages when reviewing test results, involves the simultaneous operation of duplicate samplers so that each sampler, starting at an opposite end of the transverse path, covers the total number of sampling points in a run overlapping the opposite or duplicate sampler.

SECTION 4 – INSTRUMENTS AND METHODS OF MEASUREMENT

4.1 INSTRUMENTS AND THEIR USE

4.11 Necessary Instruments

The required instruments are described in this Section. Before proceeding to select or construct instruments, those chapters of I & A dealing with these instruments should be consulted for detailed information. Many of the required conversion factors and corrections which have become standardized will be found in these chapters of I & A (Reference [6], Section 7).

The instruments and test apparatus requirements are as follows:

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

(B) Sampling apparatus consisting of nozzles, sampling probes and particulate matter collectors for proper sampling of the gas stream and collecting the particulate matter entrained therein.

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

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

(E) Thermometers or thermocouples with temperature indicator for measuring the gas temperatures at the sampling locations in the gas stream and at the orifices or gas meters.

(F) Inclined manometers or gages of equal accuracy for use with Pitot tubes in reading the 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 discharge of the metering orifice.

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

(J) A balance of suitable precision for weighing the collected particulate matter samples.

(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 minimum, higher if necessary, to meet the requirements of specific sampling conditions.

(L) Orsat apparatus, or other instrumentation of equal accuracy, for use in determining the analysis of the sample 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 I & A, PTC 19.10, Part 10, "Flue and Exhaust Gas Analysis."

(M) Stopwatch with sweep second hand (or equivalent timing devices).

(N) Barometer.

(O) Humidity measurement apparatus. The measurement of humidity and the apparatus required is covered in I & A, PTC 19.18, Part 18, "Humidity Determinations."

Illustrations of typical instruments and test apparatus are contained in the Appendix.

4.12 Isokinetic Sampling

The sampling train can use either of two methods for the maintenance of an isokinetic sampling rate.

(a) With the Pitot tube attached to the sampling probe so that the sampling rate is continuously adjusted to match the variations of gas velocity at the point of sampling. This is the preferred procedure.

(b) With the Pitot tube traverse conducted immediately prior to the actual sampling period for particulate matter so that the sampling rates for isokinetic flow are pre-calculated. This procedure may be used if the velocity fluctuations are small. See paragraphs 3.54 and 4.33b.

The Appendix contains additional information on isokinetic sampling and aids for establishing and maintaining isokinetic flow rates.

4.2 DESCRIPTION OF SAMPLING TRAIN

4.21 Filtration Section

The filtration section may be made up of the following components:

(A) A nozzle of acceptable design. See examples in Appendix B.

(B) A filter assembly, close-coupled to and immediately following the nozzle, designed for operation within the duct or stack gas stream.

(C) Where a back-up filter is used, it is preferably close-coupled to the nozzle and the primary filter so as to be completely immersed in the stack gas.

(D) Connecting tube (probe) between the filter(s) and flexible hose leading to the sample flow measurement and moisture measurement sections.

(E) As an alternative to the in-stack type filter, the primary filter (with back-up filter, if required) may be placed outside the duct or stack where temperature conditions or sampling site configuration prevents the use of an in-stack filter and appropriate precautions are taken. See paragraph 4.3. Where temperature conditions require external sample filtration, the sampling probe and tubing and the filtering system should be maintained at a temperature well above the acid dewpoint or at sufficiently high temperature to prevent condensation in the sample flow path to the filter and on the filter.

4.22 Flow Measurement and Control Section

The flow measurement and control section includes means for continuously monitoring isokinetic sampling rate and for measurement of the total quantity of gas sampled. It can be comprised of various combinations of the following components as diagramed in Appendix C and discussed in paragraph 4.3.

(A) Condenser, or impingers in an ice bath, following the filtration section for the condensation of water vapor.

(B) Desiccator, containing desiccant such as silica gel or Drierrite immediately following the condenser section.

(C) Integrating gas meter immediately following the desiccator.

(D) Integrating gas meter following the airtight pump.

(E) Orifice flowmeter, in place of integrating gas meter, ahead of vacuum source.

(F) Orifice flowmeter located after an airtight pump and used in conjunction with (C) or (D) above.

(G) Vacuum source, to induce sample flow, which may be either a pump or aspirator.

(H) Temperature and pressure gages on the metering devices and on the condenser.

Recommended arrangements of these components in the sampling systems are illustrated in Appendix C.

4.3 DISCUSSION OF SAMPLING TRAINS AND THEIR COMPONENTS

4.31 Sampling Nozzle

The nozzle size is based on measurements or estimates of gas velocities, the expected particulate matter concentration, and the desired weight of sample. The quantity of gas required to produce this weight is calculated from the expected particulate matter concentration and the desired sample weight. The size of the nozzle is calculated to give the same velocity to gases entering the nozzle as exists in gases passing the nozzle (isokinetic flow). The nozzle diameter should be as large as possible and should be of sufficient size to secure, within a reasonable time, samples large enough for accurate computation of particulate matter concentration. Nozzles smaller than 0.2 in. diameter are not recommended except for special conditions such as high gas velocities. Typical nozzle designs are shown in Appendix B.

4.32a Filter Location and Design

In a low volume sampling train, the in-stack filter has advantages over all configurations and is largely free of disadvantages. Therefore, it is the preferred method of filtration. (See Appendix A.)

If, due to excessive gas temperatures or for other reasons, it is necessary to locate the filter outside the gas stream, special precautions are necessary to prevent errors due to condensation of sulfuric acid (acid dewpoint) or of water (aqueous dewpoint) in the sampling probe and/or in the filter assembly. This can cause corrosion problems and/or result in the formation of "psuedo-particulate matter" which is not present in the gas stream at the sampling location.

The quantitative recovery of the particulate matter which is deposited in the sampling probe and in the tubing (if used) between the probe and filter presents major problems. Great care is required to insure complete removal without loss or contamination. The particulate matter removed from the probe and tubing between the nozzle and the filter must be added to the particulate matter removed by the filter(s) in the determination of the total quantity of particulate matter in the gas sample. In these manipulations, the potential for error greatly increases with increased length of probe and tubing.

The following is a listing of precautions which must be taken when exterior filters are used.

(a) The sample probe and sample tubing from the nozzle to the particulate matter collector should be smooth with no interruptions. The probe should be fabricated from a material which is the most completely resistant to corrosion or reaction in the environment being tested to avoid contamination of particulate matter which settles out in the probe. Similar precautions should be taken in the selection of sample tubing.

(b) It is imperative that the temperature of the gas sample be maintained at or above the dewpoints (aqueous and acid) or at the gas temperature at the sampling point location until it passes through the particulate matter collector(s). This requires that the portion of probe and tubing external to the stack or duct be heat insulated and provided with means for controlled heating. See Appendices A, B, and C.

(c) A temperature measuring device is required, so installed that it provides a true measurement of gas temperature through the filter. The temperature must be continuously monitored and recorded to insure satisfactory performance of the heating system in maintaining the required gas temperatures.

(d) Extra care is required for the quantitative recovery of particulate matter which is deposited in the probe and tubing. Flushing the interior with acetone, water, or other liquid is an uncertain technique for quantitative recovery. The procedures most appropriate to the sample and the sampling apparatus used must be carefully conducted to remove the deposited sample as completely as possible without contaminating it with extraneous material on the sampling train or in the atmosphere. Experience has indicated that particulate matter recovery problems can result in an "uncertainty factor" of considerable magnitude, especially with long probes.

The high volume sampling train also employs an exterior filter, but is less vulnerable to the condensation problems cited above. See Appendices A, B, and C.

4.32b Particulate Matter Filter Design

The filtering material is usually made in thimble, flat-disk, sheet, or bag form so the particulate matter can be retained in or on the filter for drying and weighing. Fiber or sintered ceramic or metallic thimbles are manufactured in relatively small sizes with a filtering capacity of 0.5 to 1.5 cu ft per minute. Flat disks, sheets and bags can be made of any size, their only limitations besides strength being that they shall be of fine enough porosity to give the required filtering efficiency, large enough to keep the resistance to gas flow within the limits of the exhausting device, and small enough to permit accurately determining their increase in mass as a result of the particulate matter caught. Since it is difficult to control the moisture content of fabric filters, it is important to make the ratio of the mass of the filter to the mass of the particulates caught as small as possible.

Keeping this mass ratio small is very difficult if the particulate sample is taken downstream of an extremely high efficiency collector. Accordingly, in such a case it is particularly important to select a filter having the least initial mass which is practicable.

Furthermore, the filter material must be completely unreactive in respect to both the particulate matter and the gas to avoid contamination of the sample. Chemical reactions of acid gases with the particles or with the alkaline filter fibers can "create" particles. With filters having mean fiber diameters less than 1μm, the absorption of water vapor can be rapid and appreciable during handling. Filter media which may possess catalytic properties in respect to the oxidation of SO_2 should be avoided. (See Section 7, References [23] and [24].)

The filtration efficiency of the filter shall be adequate to ensure that at least 99 percent by mass of all particulate matter in the filtered sample is retained on the filter. Selection and designation of the filter media should be based either on the certified filtration efficiency of the filter or upon the actual demonstrated performance of the filter under equal or more severe filtration efficiency tests. The final selection of acceptable filter media shall be a matter of mutual agreement by all parties concerned.

The filtration efficiency of a particulate filter media is a function of both the nature and concentration of the particulate matter concerned and of the duration and rate of sampling. Hence, arbitrary assignment of "filtration efficiency" ratings to a particular filter media, based upon some specified rating procedure, can be very misleading. In actual sampling practice, the true filtration efficiency achieved is usually far greater than would be indicated by the nominal "filtration efficiency" rating assigned to the filter media. This subject is thoroughly discussed in Appendix D.

4.33 Gas Flow Metering

4.33a Gas Flow Metering Devices

Gas flow metering devices can be located at any convenient place in the sample system downstream of the filter device(s) provided:

(a) Gas tight connections are maintained between the nozzle and the metering device.

(b) The device is installed to minimize turbulence (see I & A, Part 5, Chapter 4).

(c) The exhauster is airtight when the measuring device is located downstream of the exhauster.

(d) Any condensation prior to the device is measured and compensated for.

(e) Gases are dry entering the metering device or a moisture correction is determined.

The dimensional unit "micron," abbreviated "μ," refers to a dimension of 1.0×10^{-6} meters.

4.33b Regulation of Sampling Rate

The rate of sampling is usually adjusted, by a valve in the sampling system suction line, to maintain isokinetic sampling conditions. A Pitot tube near the sample point indicates gas velocity in the duct and a flow measuring device in the sampling system provides data to indicate the velocity in the nozzle.

Non-isokinetic sampling that deviates from true isokinetic conditions by more than ± 10 percent is permissible only upon the mutual agreement of all parties. With all particles present in the gas stream less than $3\mu m$ in diameter, deviations from isokinetic up to ± 30 percent may be acceptable by mutual consent. It is recognized that when the diameter of the largest particles present do not exceed $1\mu m$, errors in sample weight and composition resulting form non-isokinetic sampling rates are usually negligible. Hence, when this condition exists, non-isokinetic sampling may be considered for special circumstances by the mutual agreement of all parties concerned.

In situations where the velocity fluctuations are relatively small, a velocity traverse may be made immediately prior to the sample traverse. This method is acceptable for use in establishing isokinetic gas sampling rates if the gas flow of the process is constant within a deviation of ± 10 percent for the time duration of the Pitot tube traverse when compared to the particulate sampling period. Constancy can often be concluded by reference to the operating characteristics of the process and its exhaust fan. This can be further substantiated by process recording charts and by monitoring of fan and process draft readings.

If these records are not readily available, a monitor Pitot tube may be inserted at the representative position at the test location and velocity heads recorded at periodic intervals during the sampling period. These periodic gas velocity measurements can be compared to single point readings obtained during the traverse period, and isokinetic rates adjusted based on the single point values.

Most gas meters have dials indicating ½ to 1 cu ft. These are not considered practical for use in maintaining isokinetic flow rates in ducts with varying velocity pressures. However, gas meters are available which have dials which read to 0.02 cu ft and these can be used with a stopwatch to maintain isokinetic flow rate.

Instantaneous flow rate indicators, such as differential manometers across an orifice, are preferred and should be used with a graph or chart which relates gas velocity and density to required sampling rate in order to reduce the time required to verify isokinetic conditions. Sample flow rate should be adjusted to maintain isokinetic conditions throughout the run.

An indicating flow rate meter may be used with an integrating meter, and the flow integrated by time. Accurate time and flow rates must be used to ensure integration of the various flow rates over the test run.

4.33c Use of Metering Devices

All indicating flow meters installed in the sampling lines, for use as a guide in regulating the sampling rate or for measuring the quantity of gas sampled, shall be calibrated with a test device traceable to a National Bureau of Standards flow measuring instrument. It is not sufficiently accurate to use average handbook values for the coefficient of discharge when the orifices are small. Thin-plate orifices are usual, although thick orifices with well-rounded inlets may be employed if desired. The size of the orifice depends on the rate of sampling. In general, the orifice should be small enough to give a deflection which can be read accurately on the type of manometer used and yet not so small that the added pressure drop will adversely affect the operation of the exhausting device. If desired, the orifices can be sized to be used with the same inclined manometers as the Pitot tubes. For instructions regarding the design, installation, and use of these orifices, refer to I & A Part 5, Chapter 4, "Flow Measurements by Means of Standardized Nozzles and Orifice Plates," or refer to PTC 19.5 – 1972, "Interim Supplement on Instruments and Apparatus." The metering device can be located at any convenient place provided the precautions mentioned herein are taken. When gas meters are used they shall be calibrated at the beginning and end of the test series and whenever there is an indication that calibration may have changed. Upon completion of each test, after removal of filter, it is recommended that the sampling train be purged with clean air to recover all moisture in the train and ensure that corrosive flue gas does not remain in the train and gas meter. Flow indicators should be periodically checked for cleanliness and recalibrated at appropriate intervals.

4.34 Flow-Inducing Devices

The type of exhauster or vacuum producer is immaterial so long as it has adequate capacity. Blowers which provide a steady suction pressure and flow as well as air, water, and steam ejectors have been used. The selection of the exhauster for any particular test should be governed by the most convenient energy source available.

When the exhauster is located upstream of the measuring device, the exhauster must be an airtight device to eliminate leakage of air or other fluids into the sample gas flow. Specially constructed leakproof equipment is available for this service and is preferred. Reported errors are usually less with gas meters following these pumps than with gas meters operating under high and varying suction conditions.

4.35 Manometers

The manometers used with the Pitot tubes shall be of the inclined type graduated to 0.01 in. Magnehelic gages of comparable accuracy may also be used provided that initial calibration checks are performed. The same type can be used for the orifice differential pressure reading if the orifices are proportioned to suit. Inclined gages, whether filled with water or some other liquid, shall not require special calibration if a gage of standard manufacture is used. For description and use of manometers and Pitot tubes, refer to Test Codes for "Compressors and Exhausters" (PTC 10); "Fans" (PTC 11), (to be published); and I & A, PTC 19.2 "Pressure Measurement." When using manometers containing a liquid other than water, care shall be exercised that the density of the liquid during the test is the same as during calibration. Correction for the density of such liquids for temperature is often appreciable if the atmospheric temperature differs greatly from 68°F. When necessary, the temperature correction for density shall be applied.

If the metering orifices are designed to give a large deflection, water-filled vertical manometers may be used to measure their differential pressure. Similar manometers can be used to measure the pressure drop across the dust separator and the static pressure in the flue. The static pressure at the discharge of the metering orifices shall be measured with manometers. The divisions of any vertical manometer scale shall be checked against a machinist's scale. Sometimes scales graduated to read pressure in inches of water are used with other liquids. If a barometer is available, it should be read; otherwise a value of 29.92 in. Hg at sea level, corrected to the elevation of the test point, shall be used.

4.36 Condenser

If the dew point of the gases is above the metering temperature, a condenser should be employed, to prevent condensation in metering devices. The condenser must have sufficient storage capacity to hold the total liquid accumulation for a complete test run. The temperature of gases leaving the condenser must be measured, since this is the saturation temperature of the gases, which, together with the quantity of liquid water collected, may be used to calculate the total moisture in the flue gases.

In systems where moisture in the flue gas is derived only from fuel and air moisture, an analysis of a properly obtained sample of raw fuel will allow determinations of moisture in the flue gas. On systems such as wet scrubbers, other means must be used for flue gas moisture determination – such as a condenser system or an aspirated psychrometer.

4.37 Thermometers and Thermocouples

Thermometers, thermocouples, or thermistors are permitted under this Code if used in accordance with I & A, 19.3. If thermocouples are used in conjunction with a pyrometer or potentiometer, a comparison check with a mercury thermometer or calibration with a standard thermocouple is advisable.

When thermal stratification of gases is evident, it is recommended that the temperature of the flue gas shall be recorded at each sampling location. The temperature measuring device employed shall be attached to the Pitot tube in such a manner as not to interfere with the end openings of the Pitot tube. Flue gas temperature as recorded or monitored by process instrumentation shall not be used in sampling calculations, but shall provide a check to the measurements at the test location.

4.4 MEASUREMENT OF GAS VELOCITY

4.41 Pitot Tubes

The Pitot tubes used for measuring the gas velocities in the duct shall be of standard manufacture and certified by the manufacturer as to accuracy. Acceptable designs are contained in "Flow Meters" (6th Edition) and in PTC 19.5 – 1972. Other designs are acceptable provided the total and the static pressure serving apertures are properly designed to yield a calibration factor of unity. A type of velocity measuring device not meeting this criterion must be calibrated under conditions simulating those of the test over the full range of velocities for which it will be applied. Where gas velocity measuring devices are integral to the sampling probe, such devices must be calibrated.

4.42 Velocity Measurements

Velocity measurements are required to determine the sampling velocity at each point where the sampling nozzles are to be positioned and separately for determining the total quantity of gas passing the test section. See paragraph 3.51 for the method to be employed in determining the points where these measurements should be made.

The initial set of velocity pressure readings may be taken after the gas flow and temperature conditions have become steady, but before the start of the test run. These velocity pressure readings, together with gas temperature readings taken at the same points, may be used in determining the proper sampling rate for each traverse point.

It is often advisable to locate a Pitot tube adjacent to the sampling nozzle, for obtaining velocity pressure readings during the sampling traverse and to establish sampling rates on the basis of these readings. However, they should be so spaced that induced turbulence does not cause errors (based on prior studies to determine possible turbulence-induced interaction between sample nozzle and Pitot tube).

Where velocity measuring devices are integral to the sampling probe, separate Pitot tubes can be used in a traverse to explore the cross-sectional area velocity pattern and obtain a preliminary gas flow rate for check purposes. It may require more gas velocity measurements to obtain a true gas flow than by the positions specified for representatives sampling of particulate matter.

If the gas flow rate at the various sampling points in the duct remain reasonably constant, as determined by the monitor readings, the initial set of velocity and temperature readings by a separate traverse will suffice. If the monitor Pitot tube readings change during the sampling period, correction to the isokinetic sampling rates must be made, based upon the magnitude of the change. If any question exists during steady state processes that the gas flow rate changed appreciably during the sampling period, then a complete Pitot tube traverse should be repeated at the conclusion of the test run. If the deviation between the prior and concluding velocity traverses is greater than 10 percent, then the test run should be voided and another run conducted. In all cases, a partial traverse should be made at the end of the run to verify that flow conditions have not changed appreciably. A spare Pitot tube should be available in case of damage or trouble with those in use. See paragraph 3.11(d).

4.43 Time Measurement

Any accurate clock or watch, with a sweep second hand, is adequate for the time measurement requirements of these tests. However, a stopwatch will provide greater accuracy and convenience. Not only shall a record be kept of the duration of each run, but the movement of the sampling trains from point to point shall be kept on schedule, and any outage time for the sampling trains shall be accurately recorded. If gas flow rates are determined from an integrating gas meter, a stopwatch is a necessity.

Time recording should be coordinated between different sampling locations and test personnel. This is especially important when relating test measurements to process variables.

4.5 FILTER HANDLING AND TREATMENT OF COLLECTED PARTICULATE MATTER SAMPLES

4.51 Filter Handling

The filter media used during a test run must be oven dried to a constant mass in a heating oven and desiccated both before and after the run. The mass of sample collected on the filter will usually be quite small in relation to the mass of the filter. Therefore, it is mandatory that all precautions be taken to assure that there is no contamination of the filter media and/or sample or loss of sample during handling.

Filter specification data will generally define the best filter media for various test conditions. While the single mat-type filter offers the benefit of low tare mass and high filtration efficiency, there can be handling problems in high moisture content gas streams. The alundum thimble is an effective inert filter but it has a high tare mass and a potential for gas leakage around the edge (if improperly installed). However, if installed and used properly, it will provide high collection efficiencies that are comparable to glass fiber mat without the need for back-up filters. The following suggestions will ensure successful use of the thimble for many difficult sampling situations.

(1) Use of a medium porosity thimble.

(2) Inspect thimbles for edge defects and squareness.

(3) All new thimbles that pass inspection should be vigorously brushed, inside and out, with a hard bristle brush.

(4) The edge of a new thimble should be lightly turned on a fine sandpaper to insure good sealing, then cleaned of sanding residue.

(5) New thimbles should be fired in a muffle furnace for initial stabilization processing prior to normal weighing procedures to determine constant tare mass.

(6) New thimbles should be initially used only for high concentration particulate matter sampling. They may be used for low concentration critical sampling after a minimum of two uses on noncritical or high concentration samples.

(7) Thimbles thus processed should be used many times before discarding or as long as they remain in good physical condition. Cleaning procedures should leave the thimble in a "semi-blinded" condition which will provide a minimum pressure drop of 2 in. Hg across a well prepared thimble at normal sample gas flow rate.

(8) Two soft asbestos gaskets should be used to seal the edge of the thimble in the holder.

While filter leakage has been found to be negligible when the above procedures and precautions are applied, normal leak tests (with compensation for thermal expansion of the filter holders) must be performed when conducting sampling tests. Test the sampling system for leakage under test conditions – verifying that no decrease in vacuum occurs after a period of at least 1 min.

4.52 Weighing of Filters

Weighing with a balanced-beam chemical balance is recommended for the processing of filter media before and after sampling. The balance shall be capable of weighing to the nearest 0.1 mg. It is recommended that one person be assigned to process and weigh all samples during any given test program. The balance used shall be checked periodically for the zero setting.

4.53 Drying of Filters

The filter media should be dried to constant mass in a heating oven at a temperature which will not exceed the temperature of the test location. Heating for one hour at 105°C (220°F) is usually sufficient. Place the filter in a desiccator, containing fresh desiccant, for at least 20 min or until the filter media reaches ambient room temperature before weighing. Keep the time period for weighing the filter as short as possible. It is especially important that approximately the same weighing time is used before and after each test and that the realtive humidity of the weighing area be similar.

4.54 Removal and Processing of Deposits in Sample Probe

In most cases, the use of acetone rinsing (Reagent Grade) is the most effective way to remove particulate matter deposited in the sample probe even though this is an uncertain technique for quantitative sample recovery. The minimum amount of acetone required for complete rinsing of the probe and other sample-exposed surfaces should be used. The removal of loose deposited particulate matter and the rinsing operation should be so conducted that the possibilities for sample loss and/or contamination are minimized. Great care should be exercised to insure that the Reagent Grade acetone used does not become contaminated in any way.

Collect all loose particulate matter and acetone washings in a thoroughly cleaned sample container and seal for transporting to the laboratory.

In the laboratory, transfer the contents of the sample container quantitatively to a tared beaker and evaporate to dryness at ambient temperature and pressure. Desiccate and dry to constant weight. Weigh and report results to the nearest 0.5 mg.

4.55 Total Sample Mass

The total mass of sample collected during a run is the mass of the particulate matter collected on the filter or filters used plus the mass of the dry residue obtained from the evaporation of the acetone washings. A record shall be kept of the individual masses as well as the combined mass and this should be included in the test report.

4.6 SELECTION AND DESIGNATION OF INSTRUMENTATION AND METHODS OF MEASUREMENT TO BE USED IN TESTS

This Code contains 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. Due to the wide range of test situations which may be encountered and the limits of applicability of certain items of apparatus and method of test, great care should be taken in the selection of the appropriate apparatus and methods of tests to be used in any given test program.

Therefore, in the use of this Code in conjunction with commercial agreements and air pollution control regulations, it is necessary that the appropriate test apparatus and methods of test to be used are properly designated, or, as an alternative, the mechanisms for their designation are provided in the pertinent Contracts and Regulations.

In any case, as a consequence of the provisions of the Contracts and/or Regulations involved, the test apparatus and methods of tests to be used in a given test situation, or, for a given category of test situations, should be clearly defined and agreed upon by all parties concerned.

The following is provided for guidance and assistance in complying with the aforestated requirements when this Code is used in conjunction with commercial contracts or air pollution control regulations.

4.61 Designation of Test Apparatus

While it is desirable to designate the appropriate type of test apparatus to be used, it is practical to provide a feasible amount of leeway in respect to the detailed design of all the components and their manner of incorporation in the sampling system.

Appendix C contains illustrations of basic sampling system configurations which are recommended by this Code for various normal applications. Options are provided, both in respect to the filtration section and the gas flow control section of the train, to meet various test requirements. Numerical designations have been given to each option. These can be used for designating the type of sampling train to be used for particular test situations of concern. This can be supplemented by additional requirements and/or guidelines as appropriate to the nature of the test.

4.62 Designation of Methods of Test

After a study has been made of all the factors involved in conducting a test on specific installations or categories of process equipment, under the desired operating conditions, these factors should be utilized to define the nature of the test program which will provide the most valid and meaningful test results. The definition of the test program should include, but is not limited to the following items.

(a) Operating conditions of the installation during the tests.

(b) Number and duration of test runs.

(c) Number and location of sampling points.

(d) Methods for obtaining data on operating conditions during the test.

(e) Supplementary test data required and the means for obtaining such data.

(f) Procedures for handling test data and reporting test results.

(g) Manner of interpretation of test results for the purpose of the tests.

SECTION 5 – COMPUTATIONS OF RESULTS

This Section covers the computation of results and the preliminary computations needed to operate the test apparatus.

5.1 DENSITY OF DRY FLUE GAS

The density will be required in converting velocity head of the gas to feet per minute (meters per minute) and CFM (m^3/min) to pounds per minute (kilogram per minute) or vice versa. The density of dry flue gas can be determined from the constituents in the flue gas. With an Orsat, the percentage by dry volume of carbon dioxide, CO_2, and oxygen, O_2, can be measured when a fossil fuel is burned (see PTC 19.10). The percentage of nitrogen, N_2, is determined by difference. If complete combustion can be assumed, the volume fraction of each gas is multiplied by its respective molecular weight (MW) to determine the MW fraction. The sum of the MW fractions is equal to the dry flue gas MW. When the gas being sampled is from a noncombustion source, a knowledge of the constituents present is necessary to determine what equipment is needed to measure the concentrations.

Example:

Gas	% by Vol.	MW	MW Fraction	
CO_2	13.5	44.01	5.94	
O_2	5.2	32.00	1.66	
N_2	81.3	28.02	22.76	
			30.36	Avg. MW of dry flue gas

The density, ρ_f, is found by dividing the flue gas MW by the volume occupied by one mole of gas at the condition desired.

One pound-mole (kg-mole) will occupy 359.05 cu ft (22.415 cu m at 32°F (0°C) and 29.92 in. mercury (101.325 kPa).

$$\text{Density} = \frac{30.36}{359.05\ \text{ft}^3/\text{lb-mole}} = 0.0846\ \frac{\text{lb}}{\text{ft}^3}$$

@ 32°F and 29.92 in. Hg

$$\text{or} = \frac{30.36}{22.415\ \text{m}^3/\text{kg-mol}} = 1.345\ \frac{\text{kg}}{\text{m}^3}$$

@ 0°C and 101.325 kPa (760 mm Hg)

To adjust the density to any other temperature *T*, and pressure *P*, the density previously calculated is multiplied by the absolute temperature and pressure ratios.

Density at desired conditions = Density at standard conditions, multiplied by the temperature and pressure correction factors below.

$$\frac{(32°\text{F} + 459.67°\text{F})}{(T + 459.67°\text{F})} \text{ and } \frac{P\ \text{in. Hg}}{29.92\ \text{in. Hg}}$$

or

$$\frac{273.09°\text{C}}{(T + 273.15°\text{C})} \text{ and } \frac{P\ \text{kPa}}{101.325\ \text{kPa}}$$

5.2 MOISTURE IN FLUE GAS

The moisutre in flue gas can be calculated from the fuel analysis and the mositure in the air (refer to PTC 4.1, Section 7). There are two other prime methods for determining the moisture in the flue gas. The first is the wet-bulb and dry-bulb method (see Fig. 5-1). Information on this method is found in Instrument and Apparatus Supplement (I & A), PTC 19.18. When using the wet-bulb dry-bulb method, it is sufficiently accurate to use air-water vapor humidity charts. Humidity is a function of the molecular weight of the gas. Since the presence of CO_2 in the flue gas slightly increases the MW of the gas there is less water vapor than determined with an air-water vapor psychrometric chart. The water vapor pressure can be calculated using wet-bulb and dry-bulb temperatures and an equation developed by W. H. Carrier. This equa-

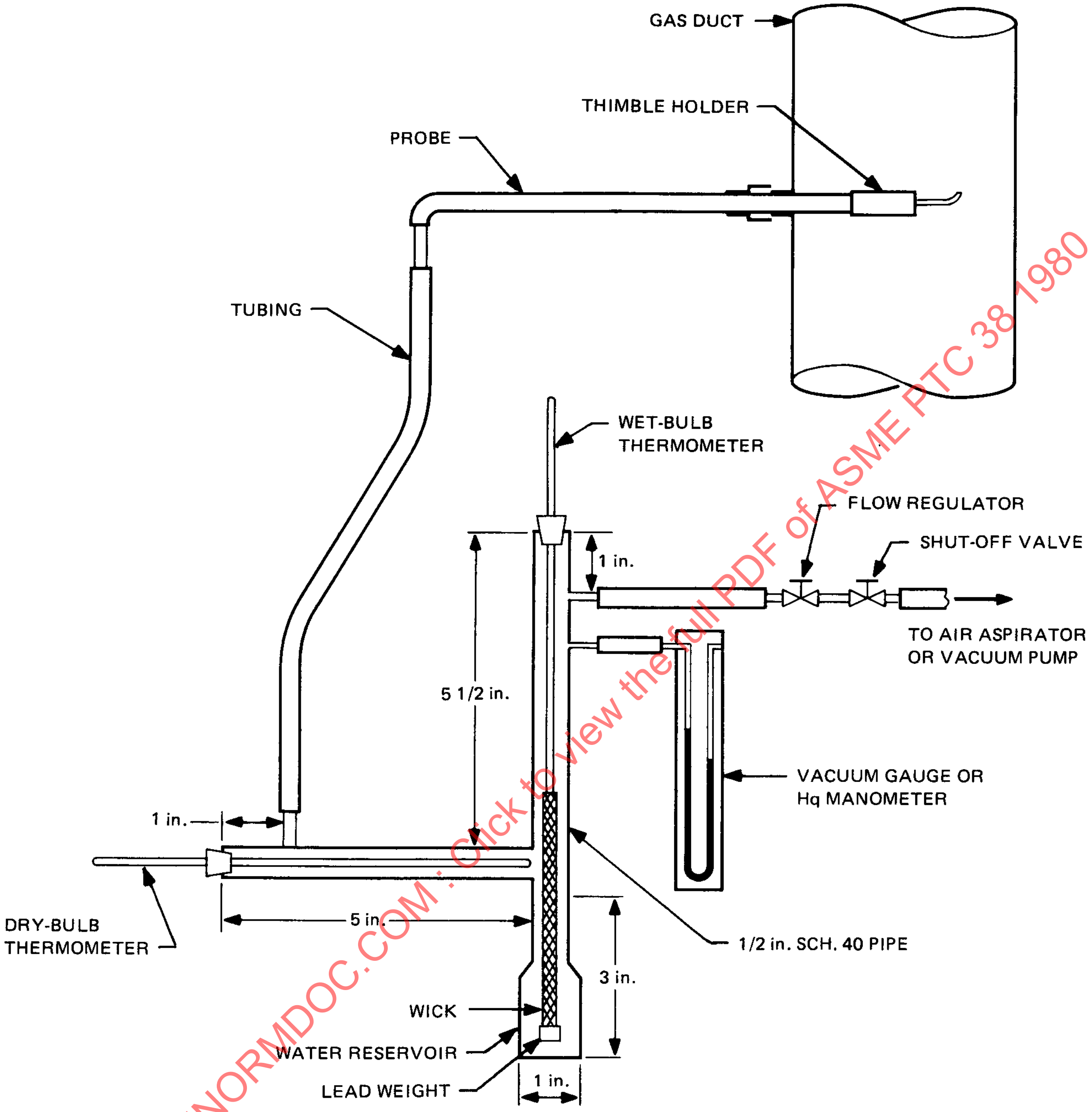

FIG. 5-1 MOISTURE DETERMINATION – WET/DRY BULB METHOD

Notes:
1. Critical dimensions only given for Wet/Dry Bulb Apparatus.
2. All tubing to be as short as possible.
3. The Wet/Dry Bulb Apparatus body must be provided with a wind barrier or insulation.

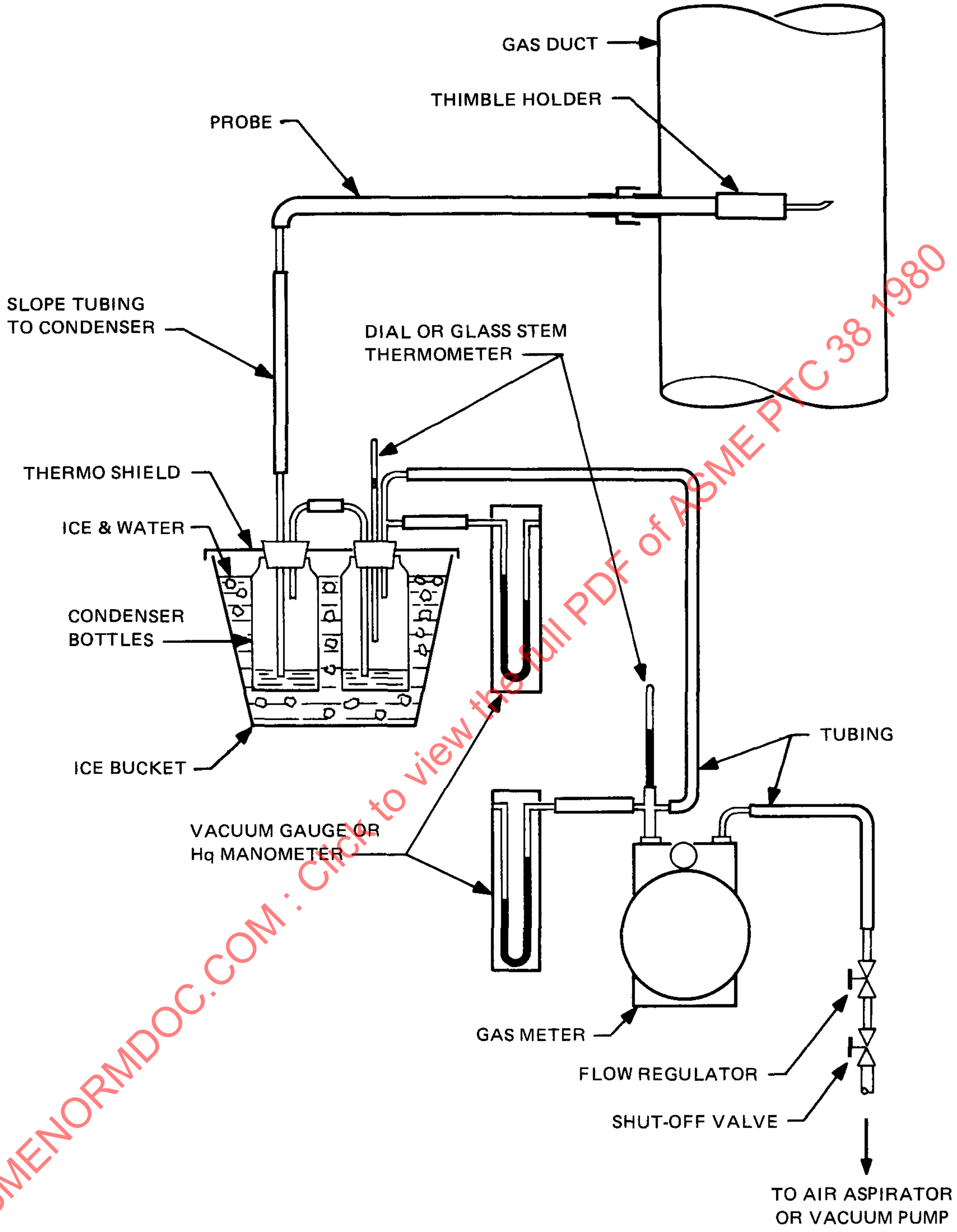

FIG. 5-2 MOISTURE DETERMINATION – CONDENSATE METHOD

Notes: 1. Laboratory condenser with accumulator may be substituted for bottles in ice bucket.
2. All tubing to be as short as possible.
3 Gas pump may be located before gas meter.

tion is explained in detail in Vol. 33 of ASME Transactions (see Reference [17], Section 7). The equation is:

$$P_{va} = P_{vw} - \frac{(P_i - P_{vw})\,(T_d - T_w)}{2800 - 1.3\,(T_w)}$$

(From PTC 19.18)

P_{va} = vapor pressure of water in the apparatus, inches HG

P_{vw} = saturation vapor pressure at T_w, inches Hg, from steam tables

P_i = average total pressure at T_w, inches Hg

T_d = dry-bulb temperature, °F

T_w = wet-bulb temperature, °F

M = percent moisture by volume in the gas

$$M = \frac{P_{va}}{P_i} \times 100$$

Example:

Total pressure at the wet-bulb thermometer is 27.64 in. mercury. The wet-bulb temperature is 120°F and dry-bulb temperature is 230°F.

$$P_{va} = P_{vw} - \frac{(P_i - P_{vw})\,(T_d - T_w)}{2800 - 1.3\,(T_w)}$$

$$P_{va} = 3.45 \text{ in. Hg}$$

$$- \frac{(27.64 \text{ in. Hg} - 3.45 \text{ in. Hg})\,(230°\text{F} - 120°\text{F})}{2800 - 1.3 \times 120°\text{F}}$$

$$P_{va} = 2.44 \text{ in. Hg}$$

$$M = \frac{2.44 \text{ in. Hg}}{27.64 \text{ in. Hg}} \times 100$$

$$M = 8.8\%$$

Water vapor can also be determined by the condensation method (see Fig. 5-2). This method can be run in conjunction with particulate matter sampling or separately. The temperature of the sampling line preceding the condenser must be kept above the water dew point to prevent condensation. The temperature (T_c) of the gas at the condenser exit must be measured if no desiccant is used. Using only a condenser, the flue gas to the metering device is assumed saturated at the temperature leaving the condenser. The percent moisture in the metered flue gas is equal to the partial pressure of water vapor divided by the total pressure multiplied by one hundred (100).

$$M_1 = \frac{P_{vw}}{P_c} \times 100$$

M_1 = percent water vapor in metered gas, by volume

P_{vw} = saturation pressure of water vapor at T_c } in consistent units

P_c = absolute pressure at the exit of the condenser } in consistent units

T_c = temperature at the exit of the condenser volume

The dry gas volume metered is equal to the wet volume measured by $1 - \frac{M_1}{100}$.

The volume of moisture collected in the condenser is usually measured in milliliters. The density of water is equal to one (1) gram per milliliter at the condition of the condenser. The volume of water collected is converted to the volume as a gas at the conditions of the gas meter.

$$\frac{\text{gm } H_2O}{453.6 \text{ gm/lb}} \times \frac{V_1}{18} = Q_1$$

= cubic feet of H_2O vapor collected in condenser at Q_1 gas meter conditions

V_1 = volume of lb-mole at the gas meter inlet temperature and pressure

When a dessicant is employed at the exit of the condenser to remove the remaining moisture, the mass of moisture is equal to the difference between the final and initial dessicant mass. The mass of water is added to the mass of water collected in the condenser for determining the volume of water vapor in the sampled flue gas. The percent moisture in the flue gas sampled is:

$$\frac{(Q_1 + Q_2) \times 100}{Q_5 + Q_1 + Q_2}$$

M_2 = percent water vapor in the total sampled flue gas

Q_1 = volume of water collected in condenser

Q_2 = volume of water in the metered gas

Q_5 = volume of dry gas metered

$Q_5 + Q_1 + Q_2 = Q_w$ = volume of wet gas sampled

5.3 DENSITY OF WET FLUE GAS

When the percent moisture in the flue gas has been determined, the percent CO_2, O_2 and N_2 on a dry basis is adjusted to a wet basis. This is done by multiplying

$$1 - \frac{\%H_2O}{100}$$ times the dry gas percentage of CO_2, O_2, and N_2. The percent moisture from wet-bulb dry-bulb example is 8.8 percent water vapor.

Gas	% by Vol. Dry	% by Vol. Wet	MW	MW Fraction
CO_2	13.5 x 0.912	12.3	x 44	5.41
O_2	5.2 x 0.912	4.7	x 32	1.50
N_2	81.3 x 0.912	74.2	x 28	20.78
H_2O	0	8.8	x 18	1.58
	100.0	100.0		29.27

The average molecular weight of wet flue gas is 29.27.

The wet flue gas denisty if found by dividing the MW by the volume of one pound mole (kilogram mole) at the conditions desired.

$$\text{Density} = \rho_w = \frac{29.27}{359 \text{ ft}^3/\text{lb-mol}} = 0.0815 \text{ lb}_m/\text{ft}^3$$

@ 32°F and 29.92 in. Hg (760 mm Hg)

$$\text{or} \quad = \frac{29.27}{22.415 \text{ m}^3/\text{kg-mol}} = 1.306 \text{ kg/m}^3$$

@ 0°C and 101.325 kPa (760 mm Hg)

5.4 VELOCITY HEAD MEASUREMENT AND VELOCITY READING

The velocity head measuring device should have a factor of one (1). If not, then the device should be calibrated in the gas stream where it is to be used. The velocity head of a gas stream is the difference between the total pressure (P_t) and static pressure (P_{sd}) in the duct. The basic equation for velocity at a point (V_n) is found in the ASME publication on Fluid Meters, Sixth Edition, page 105.

$$V_n = 96.26 \sqrt{\frac{(P_t - P_{sd})}{\rho_d}}$$

where

V_n = flue gas velocity, ft/sec
P_t = total pressure in the duct
P_{sd} = static pressure in the duct
P_{vd} = $P_t - P_{sd}$ = velocity head
ρ_d = density of the gas in the duct lb_m/ft^3

This equation is valid for 50 ft/sec (15.24 m/sec) and below. Above this value, the flue gas compressibility at the measuring device should be accounted for. When the velocity pressure is measured in inches water gage, the equation reduces to:

$$V_n = 18.27 \frac{P_{vd}}{\rho_d} \text{ ft/sec, or } 1096 \frac{P_{vd}}{\rho_d} \text{ ft/min}$$

5.5 ISOKINETIC SAMPLING

When a gas meter is used to measure total gas sampled, an orifice meter should be used as a quick means of adjusting flow rate for isokinetic conditions. The orifice meter should be designed according to criteria in the ASME publication on Fluid Meters, Sixth Edition. The meter can be calibrated against the gas meter in the same arrangement to be used for testing. The calibration should be done at five different flow rates.

$$K_n = \frac{\text{CFM} \times \rho_0}{\sqrt{h_0} \times \rho_0}$$

K_n = orifice coefficient
CFM = ft^3/min of gas passing through gas meter
ρ_0 = density of gas, lb/ft^3
h_0 = orifice differential, inches water gage

If only a gas meter is used, then the flow must be measured for a short interval of time and the flow rate adjusted accordingly. When an orifice meter is used to establish isokinetic flow, the relationship of velocity head to orifice differential is:

$$h_0 = \left(\frac{A_0 \times 1096}{k_n}\right)^2 P_{vd} \left(\frac{T_0 + 460}{T_d + 460}\right) \left(\frac{P_{sd}}{P_{s0}}\right)$$

If there is an appreciable amount of water vapor in the flue gas and a condenser is used, then the equation above should be corrected for the volume or mass flow change when the water vapor is condensed.

A_0 = area of sampler nozzle, ft^2 (m^2)
Note: ¼ in. or 3/8 in. diameter nozzles have been found suitable for most tests
T_0 = temperature of gas at orifice, °F
T_d = temperature of gas in duct, °F

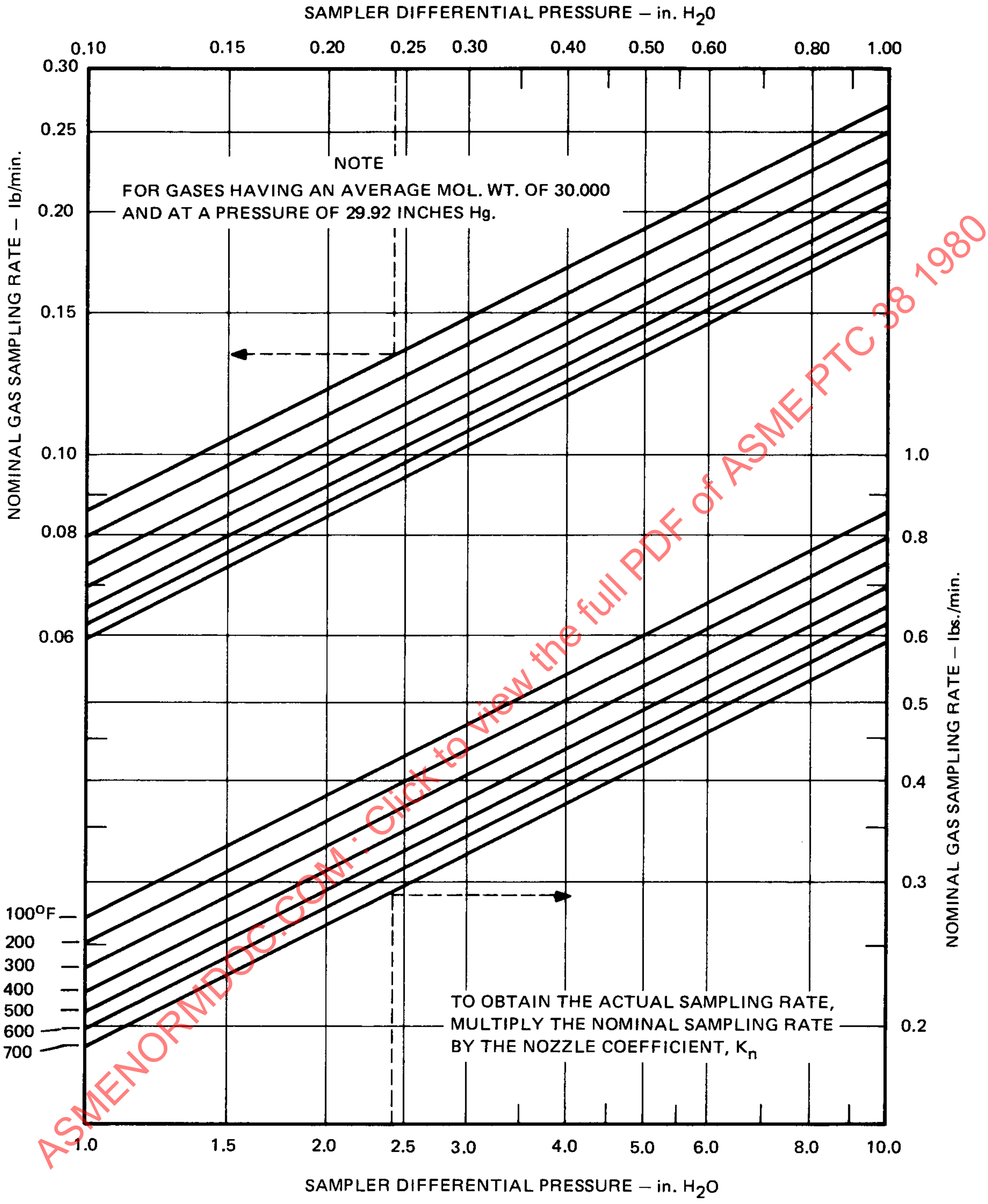

FIG. 5-3 GRAPH FOR DETERMINING NOMINAL SAMPLING RATE

P_{sd} = absolute static pressure in duct, inches Hg

P_{so} = absolute static pressure at discharge orifice inches Hg

The values of T_0, T_d, P_{sd}, P_{so}, A_0 and K_n are known, or close approximations can be made, before testing begins. A graph can be drawn relating orifice differential (h_0) to a constant times the velocity head pressure (P_{vd}).

5.6 MEASURED FLUE GAS SAMPLED ON A DRY OR WET BASIS

(A) When a gas meter is used, the volume sampled on a dry basis or wet basis is explained in paragraph 5.2.

(B) When the sampled flue gas is measured with a calibrated orifice in the portion of the probe within the flue, the flue gas is measured on a wet basis. When the orifice is outside the flue it should precede any condenser, if a wet gas rate is to be measured.

A graph can be drawn (see Fig. 5-3) assuming a coefficient (K_n) of unity from the equation

$$G = \sqrt{h_0 \times \rho_0}$$

where

G = nominal gas sampling rate, lb/min

h_0 = orifice differential, in. H_2O

ρ_0 = density at the orifice, lb/ft^3 @ 29.92 in. Hg

The nominal gas sampling rate multiplied by time sampled at a point will be nominal gas mass sampled. The sum of the nominal gas masses of all the points sampled will equal the total nominal gas mass (W_i). The total corrected gas mass is:

$$W_{wg} = K_n \times W_i \times \sqrt{\frac{P_{oa}}{29.92 \text{ in. Hg}}}$$

where

K_n = nozzle coefficient for the sampler, See Fig. 5-3

W_{wg} = total pounds of wet gas sampled

P_{oa} = average total pressure at the orifice exit, in Hg

The pounds of dry base sampled (W_{dg}) are

$$W_{dg} = W_{wg}\left(1 - \frac{\% \, H_2O}{100}\right)\left(\frac{\rho_{dg}}{\rho_{wg}}\right)$$

where

ρ_{dg} = density of dry gas, lb/ft^3

ρ_{wg} = density of wet gas, lb/ft^3

The pounds of H_2O per pound of dry gas are equal to

$$\frac{W_{wg} - W_{dg}}{W_{dg}} = \frac{\text{lb } H_2O}{\text{lb dry gas}}$$

or

$$\frac{(Q_{wg} \times \rho_{wg}) - (Q_{dg} \times \rho_{dg})}{Q_{dg} \times \rho_{dg}}$$

where

W_{wg} = total mass of wet gas sampled, lb

W_{dg} = total mass of dry gas sampled, lb

Q_{wg} = total volume of wet gas sampled, ft^3

Q_{dg} = total volume of dry gas sampled, ft^3

5.7 PARTICULATE MATTER CONCENTRATION

The particulate matter concentration is determined from the combined mass of the filter catch and recovered probe deposits which make up the total mass of the particulate matter in the quantity of gas sampled.

Particulate matter concentration is usually expressed as mass per weight of gas, mass per volume of gas, or mass per heat input. A table in the Appendix lists factors for converting from a mass per lb basis to a weight per volume basis or vice versa. When the concentration is expressed on a mass per mass basis, it is a ratio and can be expressed on any consistent unit basis lb per lb, gr per gm, kg per kg, etc. When the particulate matter concentration is to be expressed on a mass per heat input basis, the following can be used.

$$\frac{\text{lb}}{10^6 \text{ Btu}} = \frac{\text{lb particulate matter/lb dry gas} \times W_g'}{\text{Btu/lb as-fired fuel}} \times 10^6$$

$$W_g' = \frac{\text{lb dry gas}}{\text{lb as-fired fuel}} \quad \text{(see PTC 4.1, Section 7.3.2.02)}$$

$\frac{\text{Btu}}{\text{lb}}$ as-fired fuel, obtained from fuel analysis

SECTION 6 – REPORT OF RESULTS

6.1 IMPORTANCE OF REPORTS

6.11 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 operation, commercial, and/or regulatory purposes. Therefore, the accuracy and 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 operations of the emission source and emissions control systems involved. Often, tests conducted for one particular purpose are later utilized to provide useful information different in nature than that for which the test was originally conducted.

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

6.2 REPORTS AND THEIR CONTENT

A properly conducted test program should culminate in a final test report which contains the following information in a well organized format – as complete and accurate as possible.

(1) Reason(s) for conducting test and the information desired from the test results.

(2) Description of the emission source being tested, with data covering both the source itself (e.g., boiler, incinerator, etc.) and all equipment which may directly or indirectly affect test results (e.g., electrostatic precipitator, fans, etc.).

(3) 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.

(4) Identification and description of the sampling train and test procedures used with information regarding the basis of their selection.

(5) 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.

(6) Test results – both the detailed tabulation of data taken during the test and the calculated test results obtained therefrom.

(7) 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, dependent 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 objectives. These recommendations apply to a typical 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.

6.31 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 more organized test plan.

The presurvey should include the acquisition of data on the design, operation, and physical arrangement of the emission source and the related equipment of concern. This 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, 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 Figs. 6-1, 6-2, and 6-3 of this Section. 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 location, showing exact location of sampling ports, should be prepared. Actual sample point locations should be added to this when determined.

6.32 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 shown in Figs. 6-4, 6-5, and 6-6, respectively.

The data taken should not be limited to only that which may seem essential to the current objectives of the test program. Any supplementary data and observations which may later be useful should be included to the maximum extent practicable.

6.33 Operating Data

Again, the wide variation in the type of source 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 shown in Figs. 6-7, 6-8, and 6-9, respectively. These forms 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.

Where emission control systems are involved, such as electrostatic precipitators, complete operating data should be taken. For example, in the case of electrostatic precipitators, the data obtained should include (but not be limited to) the following:

(1) Physical condition of equipment during and prior to the test period.

(2) Settings and readings of all controls and instrumentation, both electrical and mechanical.

(3) Observations regarding the actual operation of the equipment involved – e.g., removal of fly ash from the precipitator hoppers, malfunction of voltage controls, air and gas leaks, etc.

(4) Meteorological data which may bear on the test results or which may bear upon the visual indication of emissions and their transport from the source into the ambient atmosphere.

6.34 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. One such form is shown in Fig. 6-10.

The primary criteria in presenting all or representative calculations in a test report are that the nomenclature and units of measurement used are defined and that the source of all input data, unfamiliar formulae, constants, and conversion factors are clearly indentified. Section 2 of the Code contains a Table of Terms which should be utilized to the maximum extent possible in the tabulation of test data and the calculation and presentation of test results.

6.35 Emission Data

Both a detailed report of the calculated emission data obtained during the test and a summary of the emission test results, correlated with pertinent operating parameters, are usually required in the final test report. A typical form for presenting detailed emission data from a combustion source is shown in Fig. 6-11 and a typical form for presenting a summary of emission test data, correlated with pertinent operating data, is shown in Fig. 6-12. Both are subject to considerable variation to meet the requirements and conditions of a specific test program.

6.36 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 be the case, the

FIG. 6-1 SAMPLE PRESURVEY FORM FOR COMBUSTION SOURCES

Name of Company

Address

Phone Person to Contact

Date of Survey By

Entry Requirements

Location and Designation of Boiler to Be Tested

Type of Boiler Capacity 10^3 lb steam/hr

Type of Fuel Steam Pressure psig

Btu Value Steam Temperature °F

Sulfur Content, % by Weight

Fuel Composition-Proximate Analysis

Fuel Composition-Ultimate Analysis

Type and Efficiency of Air Pollution Control Equipment

Is Fly Ash Reinjected?

Collection Efficiency, %

Approximate Opacity of Stack Gases, %

Normal Range of Steam Fluctuations To

Can Constant Load Be Maintained?

If So, How Long?

Conditions Under Which Boiler Can Be Tested:

Maximum Steam Load

Expected Fuel Rate

Can This Be Measured?

Excess Air Rate

Ash Withdrawal Schedule

Soot Blowing Schedule

Provide complete sketches of entire boiler and flue gas ducting. Indicate proposed locations of test points, sampling port size, location of fans, location of pollution control equipment, obstructions at sampling site, necessary scaffolding, final exit stack dimensions, location of electrical power, and type of sockets.

(Reference [30], Section 7)

FIG. 6-2 SAMPLE PRESURVEY FORM FOR INCINERATORS

Name of Company________________________________

Address________________________________

Phone________________ Person to Contact________________

Date of Survey________________ By________________

Entry Requirements________________________________

Location and Name of Unit to Be Tested________________________________

____

Type of Incinerator________________________________

Capacity,________________________________tons/hr

Type of Air Pollution Control Equipment________________________________

Collection Efficiency, %________________________________

Normal Charging Rate________________________________

How Is Charging Rate Measured?________________________________

Operating Schedule________________________________

Type and Quantity of Auxiliary Fuel________________________________

Excess Air Rate________________________________

Overfire and Underfire Air Rates________________________________

Temperature of Flue Gases at Proposed Test Points________________________________

Provide complete sketches of entire incinerator and flue gas ducting. Indicate proposed locations of test points, sampling port size, location of fans, location of pollution control equipment, obstructions at sampling site, necessary scaffolding, final exit stack dimensions, location of required electrical power, and type of socket.

Additional Desirable Information:

Refuse Analysis, if Available________________________________

Approximate Opacity of Stack Gases________________________________

Normal Variations in Charging Rate________________________________

Residue Removal. Method________________________________

Schedule________________________________

Where and How Temperature Are Measured Through System________________________________

(Reference [30], Section 7)

FIG. 6-3 SAMPLE PRESURVEY FORM FOR INDUSTRIAL PROCESSES

Name of Company

Address

Phone Person to Contact

Date of Survey By

Entry Requirements

Type of Process

Location of Process

Operating Schedule

Process Description

Process Feed Rates

Expected Emissions

Type	Concentration	Quantity

Type and Efficiency of Air Pollution Control Equipment

Opacity of Exit Gases

Expected Stack-Gas Parameters at Test Location

Temperature, °F

Pressure, psig

Volume, acfm

Composition, % H_2O

% N_2

% O_2

Ambient Conditions at Test Site(s)

Temperature

Noxious Gases

Weather Protection

Required Safety Gear

Provide complete sketches of entire process and exit gas ducting. Indicate proposed locations of test points, sampling port size, location of fans, location of pollution control equipment, obstructions at sampling site, necessary scaffolding, final exit stack dimensions, location of electrical power, and type of sockets, location and nature of water supply.

(Reference [30], Section 7)

FIG. 6-4 SAMPLE FORM FOR GAS VELOCITY AND VOLUME DATA

Test No.______

Location______

VELOCITY TRAVERSE DATA

Point	Position, inches[a]	Reading, Δp inches of H_2O	$\sqrt{\Delta p}$	T_s, °F
Total		______		
Average		______		

[a] From outside of port to sampling point.

Pitot tube______

Manometer______

Thermometer______

Stack Inside Dimensions______

Stack Area = ______ ft²

Barometric Pressure, P_b = ______ in. Hg,

Stack Gauge Pressure = ______ in. H_2O

Stack Abs. Pressure, P_s = ______ in. $\frac{H_2O}{13.6}$ + P_b = ______ in. Hg

Stack Gas Temp., T_s = ______ °F + 460 = ______ °R

Molecular Weight of Stack Gas, M_s = ______

1. $V_s = 174\,C_p \sqrt{\Delta p T_s \times \frac{29.92}{P_s} \times \frac{28.96}{M_s}}$

   V_s = ______ ft/min

2. Volume = ______ ft/min × ______ ft² = ______ ft³/min

   Standard Volume at 70°F and 29.92 in. Hg:

3. ft³/min $\times \frac{530}{T_s} \times \frac{P_s}{29.92}$ = ______ $\times \frac{530}{\_\_\_\_} \times \frac{\_\_\_\_}{29.92}$ = ______ sCFM

Date Recorder______

Date______

(Reference [30], Section 7)

FIG. 6-5 SAMPLE FORM FOR FIELD SAMPLING METER DATA

Plant__________

Run Number__________

Location__________

Date__________ Time__________

Operator__________

Sample Box Number__________

Meter Box Number__________

Δ H@__________

Filter No.__________

Barometric Pressure, in. Hg__________

Assumed Moisture, %__________

Assumed Meter Temp., °F__________

Stack Gauge Pressure, in. H_2O__________

Probe Tip Diameter, in.__________

'C' Correction Factor__________

Point	Time, min.	Dry Gas Meter			Velocity Head Δp, in. H_2O	Orifice ΔH, in. H_2O	Pump Vacuum, in. Hg	Box Temp., °F	Impinger Temp., °F	Stack Temp., °F
		Volume, ft^3	Inlet Temp., °F	Outlet Temp., °F						

COMMENTS:

Leakage Rate @______in. Hg =______

(Reference [30], Section 7)

FIG. 6-6 SAMPLE FORM FOR PARTICULATE MATTER ANALYSIS DATA

WEIGHT OF PARTICULATE MATTER COLLECTED

Field Container Number	Total Final Weight, mg	Tare Weight, mg	Weight Gain, mg
Pri. Filter No.		________Filter ________Container	
Sec. Filter No.			
Nozzle No.			
Probe Wash No.			
No.			

Plant____________________

Run. No.____________________

Location____________________

Received from________ Received by________

Analyzer____________________

Date Analyzed____________________

Total Weight of Particulate Matter Collected, W_p = $\times\ 2.2 \times 10^{-6}$ = lb

$\times\ 15.4 \times 10^{-3}$ = gr

VOLUME OF MOISTURE COLLECTED

	Final Volume, ml	Initial Volume or Weight	Volumetric Gain, ml
Impingers		−200 ml	
Silica Gel Container No.		− g	

Total Volume of Water Collected, V_T = ml × 0.047 = scf

(Reference [30], Section 7)

FIG. 6-7 SAMPLE FORM FOR BOILER OPERATING DATA

Test No.____________________ Date____________________

Name of Company____

Location and Description of Boiler________________________________

____

Type of Boiler____________________ Capacity____________________1000 lb steam/hr

Type of Fuel____

Date Recorder____

Time____

Fuel Rate

Steam Rate
1000 lb/hr

Combustion
Air Rate,
1000 lb/hr

% Excess Air
Flue Gas Analysis:
% O_2
% CO_2

Steam Pressure

Steam
Temperature

I.D. Fan, rpm

Firing Data:
Oil Pressure (if oil fired)
Oil Temperature (if oil fired)
Burner Tilt
Windbox Damper Settings

I.D. Fan, amps

Pressures, in. H_2O

Furnace Outlet
Collector Inlet
I.D. Fan Inlet

Plume Opacity

Fuel Composition (As Weighed),
Btu/lb
% Moisture

Ultimate Fuel Analysis

% Ash

% *S*

% Volatile Matter

% Fixed Carbon

(Reference [30], Section 7)

FIG. 6-8 SAMPLE FORM FOR INCINERATOR OPERATING DATA

Test No.________________________________ Date________________________

Name of Company____

Location and Designation of Unit_________________________________

____

Type of Incinerator____

Type of Control Equipment_____________________________________

Type of Grate____

Grate Speed____

Type of Refuse Burned____

Approximate Moisture Content__________________________________

Data Recorder____________________

Time	Material Charged, lb	Primary Chamber Draft		Secondary Chamber		Plume	I.D. Fan	
		Overfire, in. H_2O	Underfire, in. H_2O	Draft, in. H_2O	Temp., °F	Opacity %	rpm	amp
Tot.	Tot.	Avg.	Avg.	Avg.	Avg.	Avg.		

% of Time Afterburners Are in Operation________________, if used.

Fuel Rate to Afterburner________________, if used.

Plume Observer:________________________

Certification:________________________

(Reference [30], Section 7)

FIG. 6-9 SAMPLE FORM FOR PROCESS OPERATING DATA

Test No.____________________ Date____________________

Name of Company____________________

Location and Description of Process____________________

____

Capacity and Characteristics of Process and/or Product____________________

____

____

____

Raw Materials____________________

Fuel Used____________________

Time	
Raw Material Feed Rate	
Fuel Rate	
Reactor Temperature	
Reactor Pressure	
Product Rate	
Sidestream Rates	
Recycle Stream Rates	
Exit Plume Opacity	

(Reference [30], Section 7)

FIG. 6-10 SAMPLE FORM FOR SAMPLING CALCULATIONS

Plant No. ____________________ Calculated by ____________________

Run No. ____________________ Checked by ____________________

Location ____________________ Date ____________________

Meter Volume ____________________

Leakage Volume ____________________ (Leakage rate × sampling time)

Net Sample Volume, Q_m ____________________ ft³

Average Meter Temperature, T_m ____________ °F + 460 = ____________ °R

$P_m = P_b =$ ____________________ in. Hg

Standard Sample Volume,

$Q_{ms} = 17.7 \times Q_m \times \dfrac{P_b}{T_m} = 17.7 \times$ ____________ × ____________ = ____________ ft³

Equivalent Moisture Volume, $Q_v =$ ____________________ scf (Fig. 6-6)

Total Sample Volume, $Q_t = Q_{ms} + Q_v =$ ________ + ________ = ________ scf

Particulate Sample Weight, $W_p =$ ____________ gr (Fig. 6-6)

Particulate Concentration, $C = \dfrac{\text{\_\_\_\_\_\_\_\_\_\_}}{Q_t} =$ ____________ gr/scf

Particulate Concentration,

dry basis $C_d = C \times \dfrac{100}{100 - W} =$ ____________ gr/dry scf

where: W = % moisture in flue gas

Emission Rate,

lb/hr, $E = C \times Q_{ss} \times 0.00857 =$ ____________ × 0.00857 = lb/hr

where: Q_{ss} = total flue gas flow rate in ft³/min

$$\% \text{ Isokinetic, } I = \frac{V_s}{\dfrac{Q_t}{t \times A_n} \times \dfrac{T_s}{530} \times \dfrac{29.92}{P_b}} \times 100 = \text{\_\_\_\_\_\_\_\_\_\_}\%$$

where:

t = sample time, min

A_n = area of sample nozzle, ft²

V_s = stack-gas velocity, ft/min (Fig. 6-4)

(Reference [30], Section 7)

FIG. 6-11 SAMPLE FORM FOR PRESENTING EMISSION DATA — COMBUSTION UNIT

Test No.	Steam Rate, 1000 lb/hr	Fuel Rate	Flue Gas				Particulate Matter		
			Volume, scfm[a]	Temp., °F	% CO_2	% H_2O	gr/scf	lb/1000 lb	lb/10^6 Btu

[a]Standard cubic feet per minute at 70°F and 29.92 in. Hg.

(Reference [30], Section 7)

FIG. 6-12 SAMPLE FORM FOR SUMMARY OF EMISSION TEST DATA

Test No.
Date
Name
Address

Process Tested

1. Sampling Station
2. Material Collected
3. Operating Condition
4. Avg. Flue Gas Velocity, ft/min
5. Avg. Flue Gas Temp., °F
6. Area of Duct, ft^2
7. Gas Flow Rate, scfm
8. Sampling Nozzle Diam., in.
9. Avg. Meter Sampling Rate, ft^3/min
10. Testing Time, min
11. Avg. Meter Temp., °F
12. Sample Gas Vol.— Meter Cond., c^3
13. Sample Gas Vol.— Standard Cond., scf
14. Water Vapor Condensate, ml Volume, scf
15. Total Sample Gas Volume, scf
16. Weight Collected, grams
17. Total Weight, *g*
18. Concentration, gr/scf
19. Concentration, gr/scf @ 12% CO_2
20. Concentration, % by volume
21. Concentration, ppm by volume
22. Emission Rate, lb/hr

COLLECTOR EFFICIENCY

23. Material to Collector, lb/hr
24. Loss to Atmosphere, lb/hr
25. Efficiency, %

Test Conducted by
Analysis by
Calculations by

(Reference [30], Section 7)

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.

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  PTC 19.3 – "Temperature Measurement"
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SECTION 8 – APPENDIX

8.1 INDEX TO APPENDIX

Designation	Subject
A	Design and Selection of Sampling Trains
B	Sampling Probes and Particulate Matter Collection Apparatus
C	Particulate Matter Sampling Systems
D	Filtration Efficiency of Filters for Fine Particulate Matter
E	Sampling in Low Velocity Gas Streams
F	Particulate Matter Collection and the Effect of Condensed SO_3
G	Typical Gas Velocity and Particulate Matter Concentration Profiles
H	Methods for Determining Number and Location of Sampling Areas
I	Instrumentation for Determining Gas Velocity
J	Design and Construction of Field Operating Graphs
K	Graphs and Tables of Useful Data
L	SI System for Units of Measurement

APPENDIX A

DESIGN AND SELECTION OF SAMPLING TRAINS

A wide variety of apparatus assemblies can be envisioned, all of which would be equally capable of accurate sampling of particulate matter in a normal gas stream. The differences between them will be in their relative convenience as to portability, assembly, and handling during operation when used in a wide variety of sampling situations and in their relative potential for inducing accidental or systematic error.

Individual preferences, based on personal familiarity with a particular apparatus or other subjective criteria, will have some influence in the selection of sampling apparatus. Nevertheless, there are important differences of a practical nature between them which are important to recognize. These are set forth in the following comparisons of the three principal categories of sampling train design:

A. High volume sampling train.
B. Low volume sampling train with exterior filter.
C. Low volume sampling train with in-stack filter.

A. HIGH VOLUME SAMPLING TRAIN

Sampling trains in this category may handle, typically, 5-10 to 40-50 CFM, using sample probe tubing of ¾ in. to 1¼ in. diameter. The filters are usually located outside of the duct or stack.

Advantages

(1) The high ratio of sample gas flow rate to sampling system wall area minimizes the errors due to loss of particulate matter on the tubing walls between the nozzle and the filter. Hence, the special precautions necessary to avoid errors from this cause are minimized to some extent.

(2) Heat losses from the sample gas stream in passing through the connecting tubing, for the same reason, are small relative to the total heat content of the sample gas stream – making it easier to maintain the temperature of the gas stream above the dewpoint.

(3) A null pressure nozzle can be applied to the characteristically large diameter tubing more successfully than to the small tubing.

(4) The greater quantity of sample collected per unit of time reduces the relative magnitude of errors resulting from sample handling, weighing, etc.

Disadvantages

(1) Its greater mass and bulk may be inconvenient as to transportation and to manipulation during the test, especially where very long sample probe tubing is required as in the case of large diameter stacks.

(2) Where cooling of the gas stream is required, the auxiliary cooling apparatus required may be an added inconvenience due to its larger size and coolant media requirements. Such cooling may be required to protect the filter assembly against excessive temperature or to provide a cooled sample for special research investigations.

B. LOW VOLUME SAMPLING TRAIN WITH EXTERIOR FILTER

In this type of train, the sample probe extends from the interior of the duct being sampled to an outside filter. The sample gas flow rates are usually in the range of ½ to 1½ CFM, using sample probe tubing of ¼ in. to 5/8 in. in diameter.

Advantages

(1) Where the very high stack gas temperatures exceed the limits of the sample filter assembly (filter media, gaskets, machine threads, etc.) or where it is desired, in special investigations, to cool the sample gas, this can be accomplished easily in the train by the passage of the gas through the exterior sample tubing between the stack or duct and the sample filter assembly. Auxiliary cooling systems, if required, will be smaller in size and have lower coolant media requirements.

Disadvantages

(1) The major disadvantage of this type of sampling train is that relatively appreciable quantities of the particulate matter in the sample gas are inevitably deposited in the sample probe tubing between the nozzle and the sample filter assembly, and these must be quantitatively recovered from the tubing and added to the material collected in the filter. There is an inherent error in this manipulation for sample recovery which is aggravated in those cases where long sample probe tubing is employed and where the particulate matter concentrations are low.

(2) The low ratio of sample flow rate to the wall area results in very rapid cooling, and if not prevented, may reduce gas temperature below the dewpoint and create corrosion of the tubing material (even stainless steel), plug the filter with condensed water, or create pseudo-particulate matter – e.g., sulfuric acid aerosol from sulfur trioxide or, possibly, sulfuric acid from the oxidation of sulfur dioxide within the sampling train due to the nature of the sample gas, the particulate matter, and the surface conditions to which the sample is exposed within the train.

(3) The potential problems listed above require the use of auxiliary facilities to heat the connecting tubing and devices for temperature control which can be quite cumbersome to handle and operate, particularly where long sample probe tubes are necessary.

Despite the disadvantages of low volume sampling trains with exterior filters, there are two test situations where their use can be justified.

One situtation is where the flue gas temperature is higher than can be tolerated by the filter assembly. In this case, the gas sample temperature is lowered to tolerable levels by exterior cooling prior to filtration.

In another situation, two filters would be used – one, an in-stack filter, and the other, an exterior filter, with facilities for accurately controlling the sample gas temperature between the two filters. This arrangement might be used in special studies to measure the presence of condensible vapors. The in-stack filter would yield data on concentrations of particulate matter actually in the flue gas and the exterior filter, always maintained at temperatures above the aqueous dewpoint, could collect liquids and solids formed by condensation in the sampling system between the two filters. This type of study is outside the scope of this Code.

C. LOW VOLUME SAMPLING TRAIN WITH IN-STACK FILTER

This is the same assembly as that of category B above in respect to sample flow rates and the size of tubing – differing in that the filter holder, of compact dimensions, can be easily inserted through a sample port and be positioned inside the duct or stack during sampling – completely immersed in the main gas stream and maintained automatically at the gas stream temperature.

Advantages

(1) Substantially all the particulate matter is deposited directly in the filter since there is scarcely any tubing between the point of entry of the sample gas stream and the filter proper.

(2) Because the filter is automatically maintained at the same temperature as the flue gas, no auxiliary apparatus is required for regulation of the temperature of the filter and sample probe tubing. This results in a smaller and lighter weight sampling train, unencumbered with a temperature control system which would require attention during the test.

Disadvantages

This type of sampling train has fewer significant disadvantages than those of the other two types – and for this reason is the one favored in this Code.

(1) Sampling situations may be encountered where the gas temperature exceeds that which can be tolerated by the filter and filter holder, as alluded to previously.

(2) The in-stack filter would not yield data on the concentration of particulate matter formed as a result of cooling the flue or stack gases. This would actually be an advantage when it is desired to measure only the concentration of the particulate matter actually existing in the flue gas stream.

(3) Thermal expansion of the filter holder during high temperature sampling may create gas leakage problems if adequate precautions are not taken.

D. SUMMARY AND CONCLUSIONS

(1) The detailed specification of one particular sampling train and the procedure for its use is not a guarantee of valid test results, and therefore is not an appropriate foundation for test codes – particularly for their use in connection with governmental regulations and commercial agreements. This has been demonstrated in numerous published experiences in the field of stack sampling.

(2) All types of sampling trains (high-volume and low-volume, with in-stack and/or exterior filters) should give the same test results if one copes successfully with the error-inducing hazards listed below in the approximate order of their relative importance.

(a) Overcome difficulties in sampling a large duct area, with the inherent tendency toward particulate matter stratification, by all techniques available to insure a representative sample.

(b) Maintain the temperature of the filter and the upstream sample probe tubing above the aqueous and acid dewpoints – using the appropriate instrumentation to verify the accomplishment of this objective. Simply heating the chamber enclosing the filter is not an acceptable means for accomplishing this.

(c) Insure quantitative recovery of all material deposited in the nozzle, probe, and tubing preceding the filter – avoiding potential losses (due to manipulative problems) or spurious material (due to corrosion, sulfate formation, or contamination). These problems are enhanced by long tubing and high dewpoints.

(d) Maintain an isokinetic sampling rate and an effective system for its monitoring.

(e) Obtain reliable measurement of total gas flow, especially in large area ducts and where there is a tendency toward maldistribution of velocities.

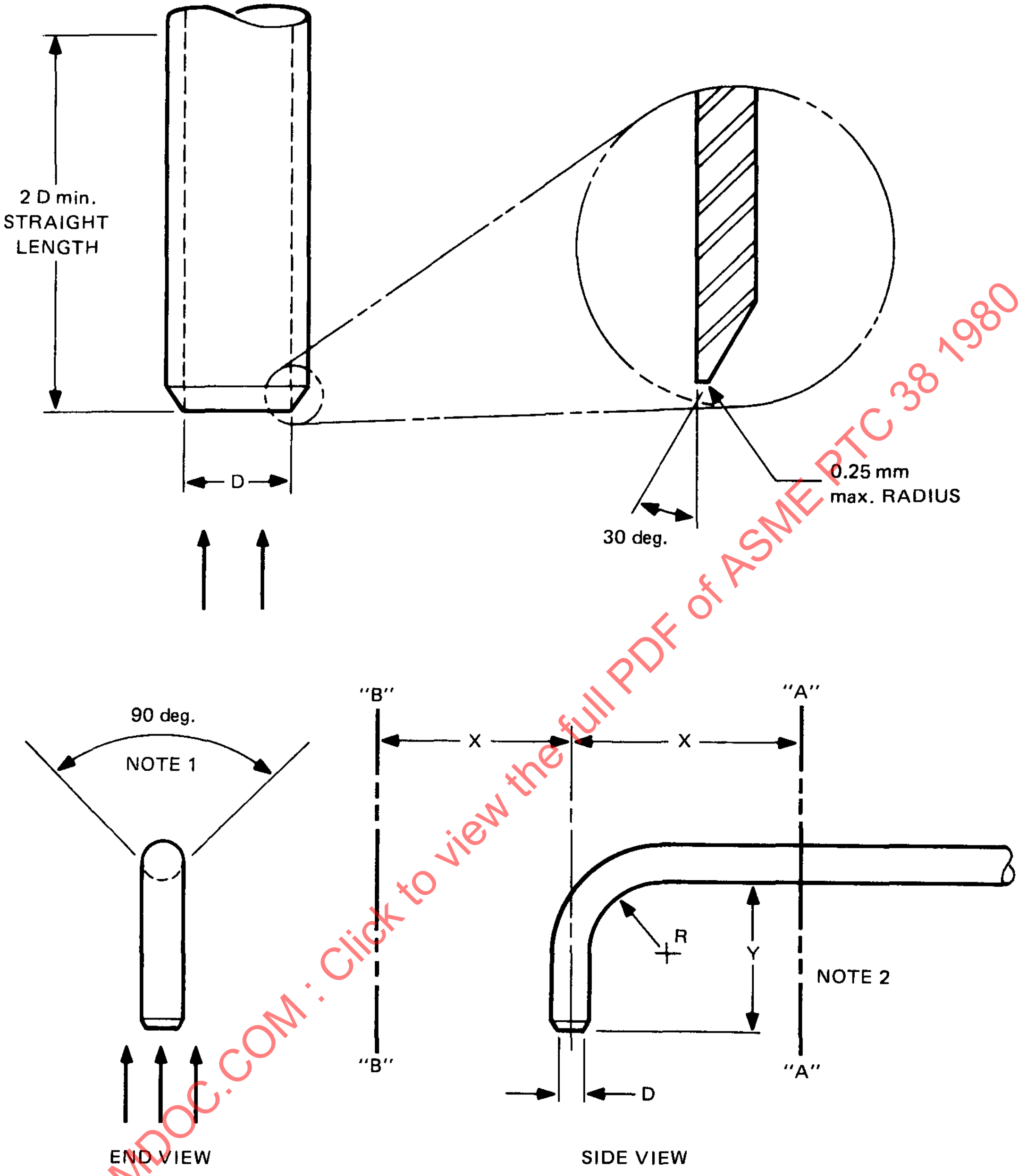
Note: Sampling train configurations, along with auxiliary apparatus for all of the types of trains discussed, are illustrated in Appendix C.

APPENDIX B

SAMPLING PROBES AND PARTICULATE MATTER COLLECTION APPARATUS

There are many different types of sampling probes and particulate matter collection apparatus available for use in the collection of gas-entrained particulate matter from a stack or duct. This Code provides guidance for the selection of the most appropriate sampling system components for use in any particular sampling situation.

On the following pages are illustrations of typical sampling probes and particulate matter collection devices which are commercially available. Further information regarding these sampling system components and their use can be obtained from the manufacturer.



Notes: 1. The area upstream of this 90° sector shall be free of obstructions between planes A-A and B-B.

2. No portion of probe shall project upstream of nozzle entrance within a distance from nozzle centerline of 15 cm or 5 nozzle diameters, whichever is greater.

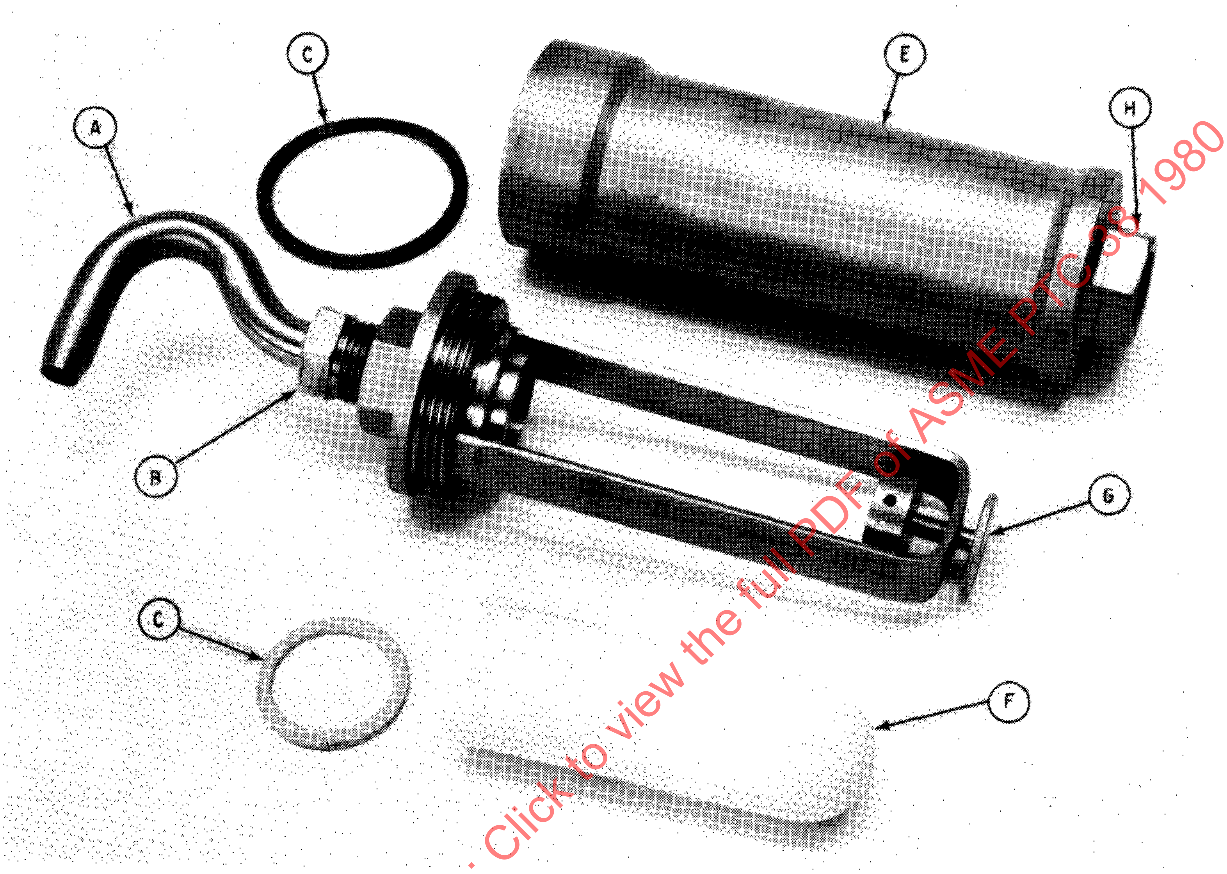
D = Nozzle Diameter

R = 2 X D (Minimum)

Y = 4 X D (Minimum)

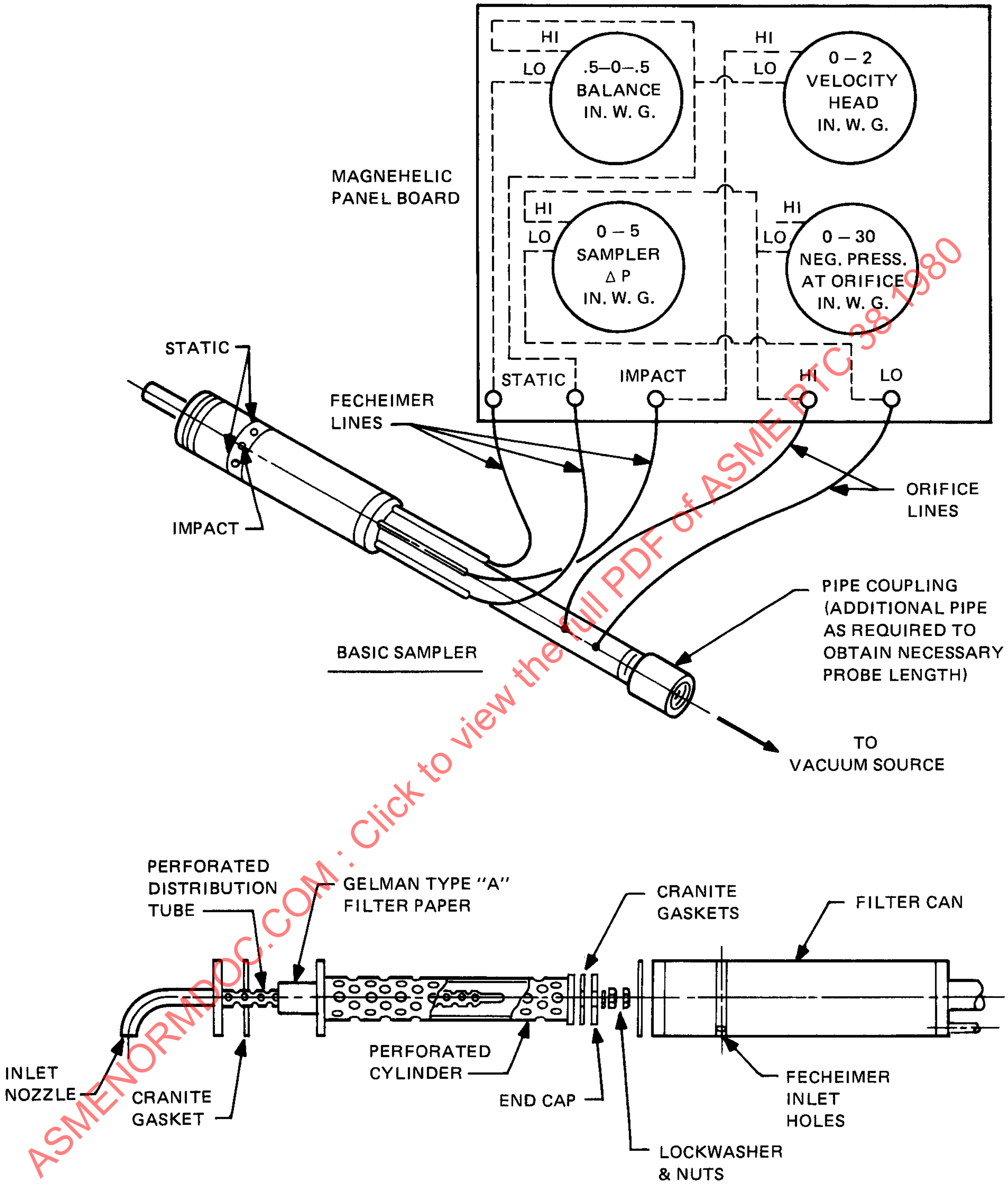
X = 6 X D (Minimum)

FIG. B-1 RECOMMENDED DESIGN FOR SAMPLING NOZZLE TIP



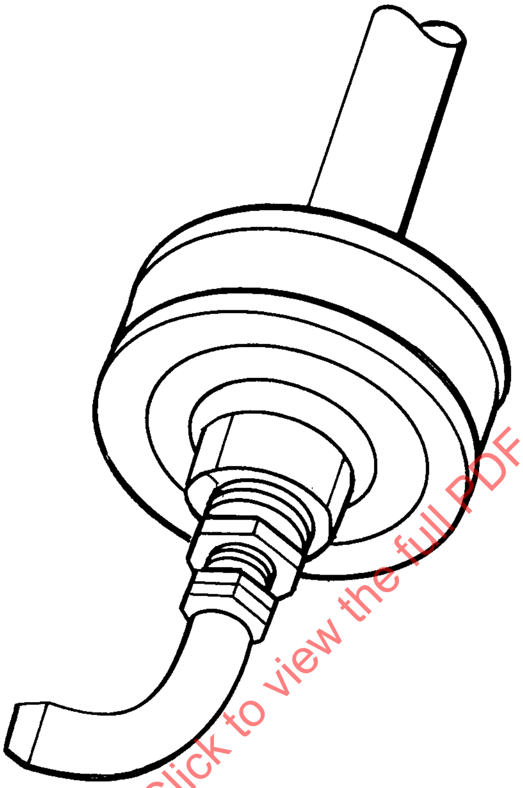
Code	Part Identity and Function
	Complete Assembly, including Alundum Thimble
A	Probe Tips (1/4, 3/8, & 1/2" ID nozzles: 1 each)
B	Fitting (adapts nozzles to holder)
C	Asbestos Gaskets
D	Guide Ring
E	Housing
F	Alundum Thimble
G	Clamp
H	Adapter (adapts holder to probe)

FIG. B-2 ALUNDUM THIMBLE PROBE



(ALTERNATE—END CAP WELDED TO PERFORATED CYLINDER)

FIG. B-3 IN-STACK FILTER ASSEMBLY USING PAPER FILTER MEDIA



Suitable for use as In-Stack Primary Filter,
Back-up Filter, or Exterior Filter

FIG. B-4 TYPICAL HOLDER FOR FLAT ROUND FILTERS

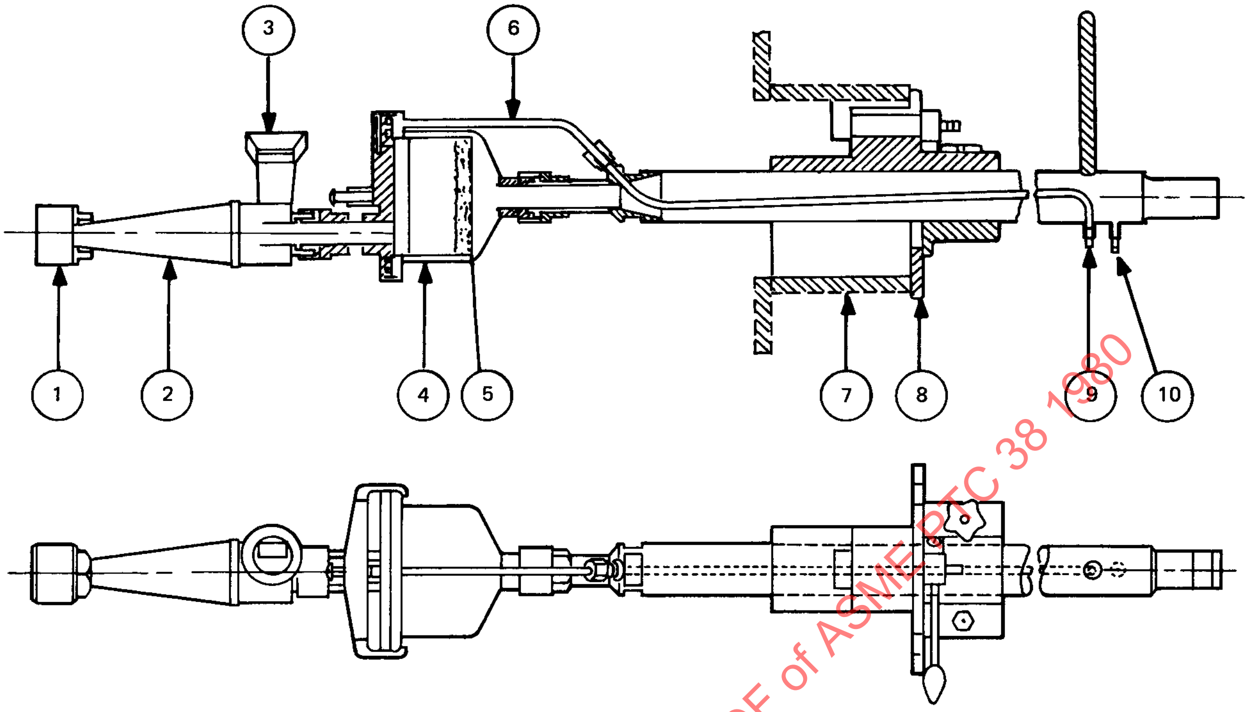


FIG. B-5a BCURA CYCLONE PROBE – INTERNAL TYPE, INCLUDING FILTER

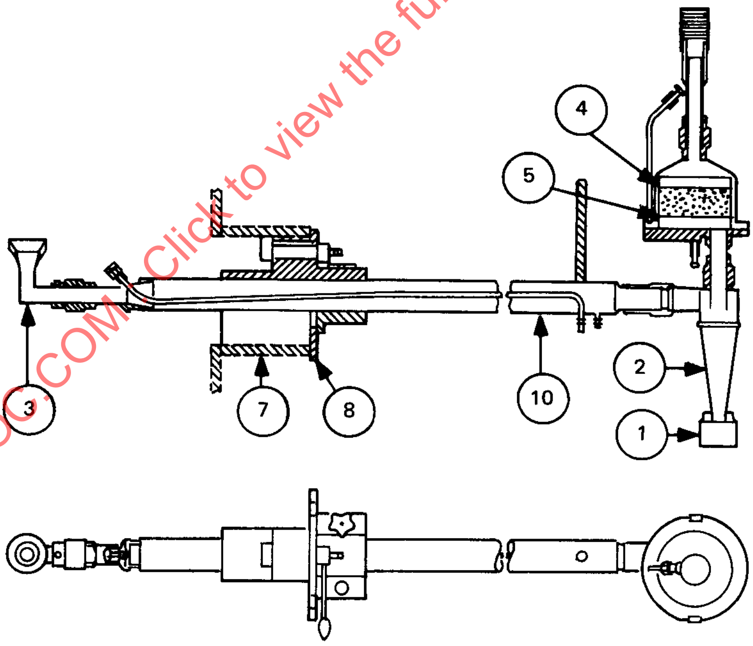


FIG. B-5b BCURA CYCLONE PROBE – EXTERNAL TYPE, INCLUDING FILTER

Key to Figs. B-5a and B-5b

(1) Hopper for collecting large particles (2) Cyclone (3) Sampling nozzle (4) Filter housing (5) Filter, packed with glass wool, for collecting particulate matter (6) Filter by-pass pressure tube (7) 4-in. B.S.P. socket welded to wall of flue (8) Probe holder (9) Tapping for measuring cyclone pressure drop when filter is used (10) Tapping for cyclone pressure drop when filter is omitted

Note: See Reference [32] in Section 7.

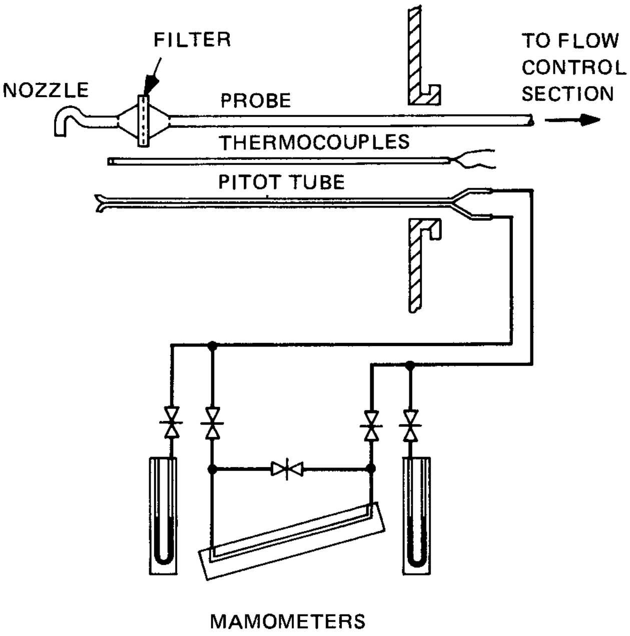
APPENDIX C

PARTICULATE MATTER SAMPLING SYSTEMS

This Code provides guidance both for the selection of sampling system components and the manner in which they should be used in any particular sampling situation. Many different types of sampling systems are possible, depending upon the components selected and their arrangement to best provide valid sample data in as convenient a manner as possible.

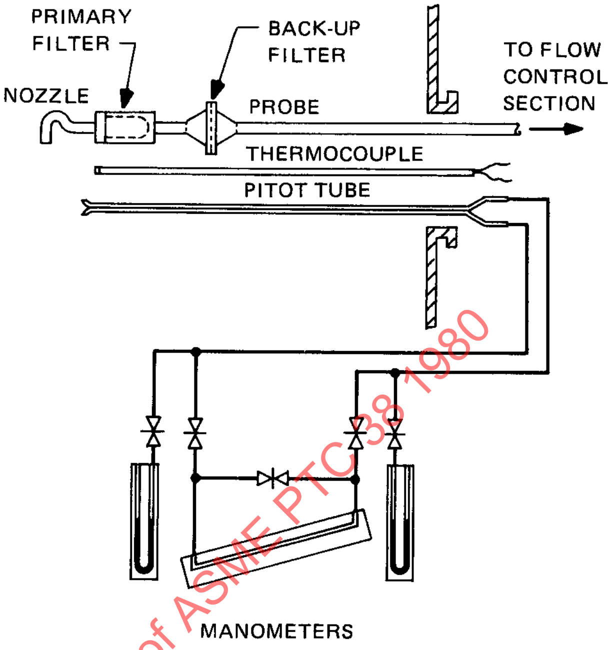
The following pages contain illustrations of sampling system configurations recommended in this Code for various sampling applications. Also included are sampling system configurations which are not recommended but are acceptable in certain special test situations.

Type 1. (Low Volume)



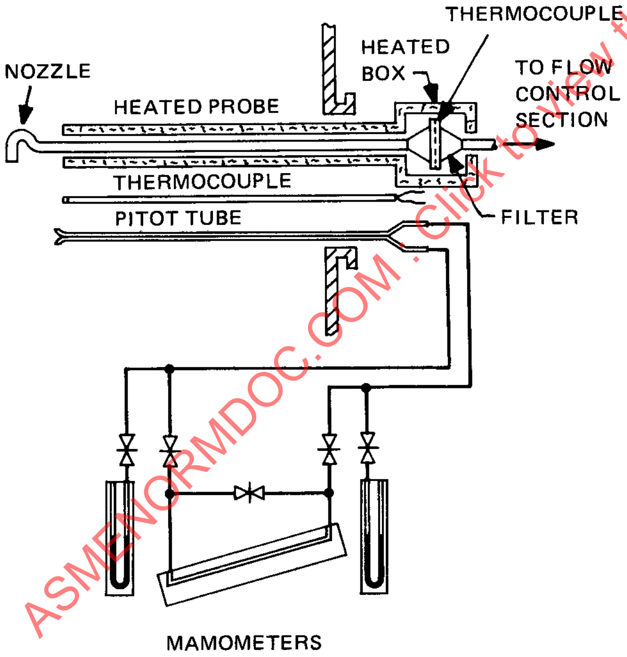
Recommended for general use – low particulate matter concentrations.

Type 2. (Low Volume)



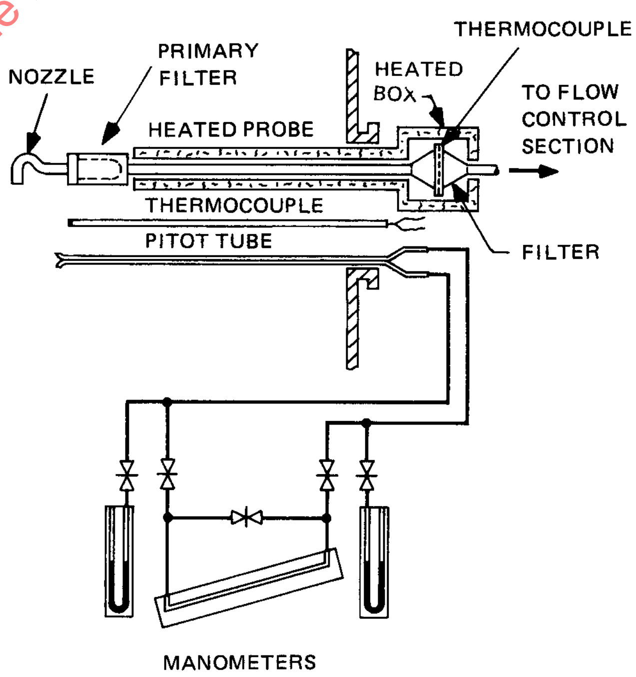
Recommended for general use – higher particulate matter concentrations.

Type 3. (Low or High Volume)



Recommended for use only when in-stack filters cannot be used due to high gas temperatures or other special considerations.

Type 4. (Low Volume)



Acceptable for special cases (higher particulate matter concentrations) when an exterior heated filter is required. Type 1 in-stack filter may be used when particulate matter concentrations are low.

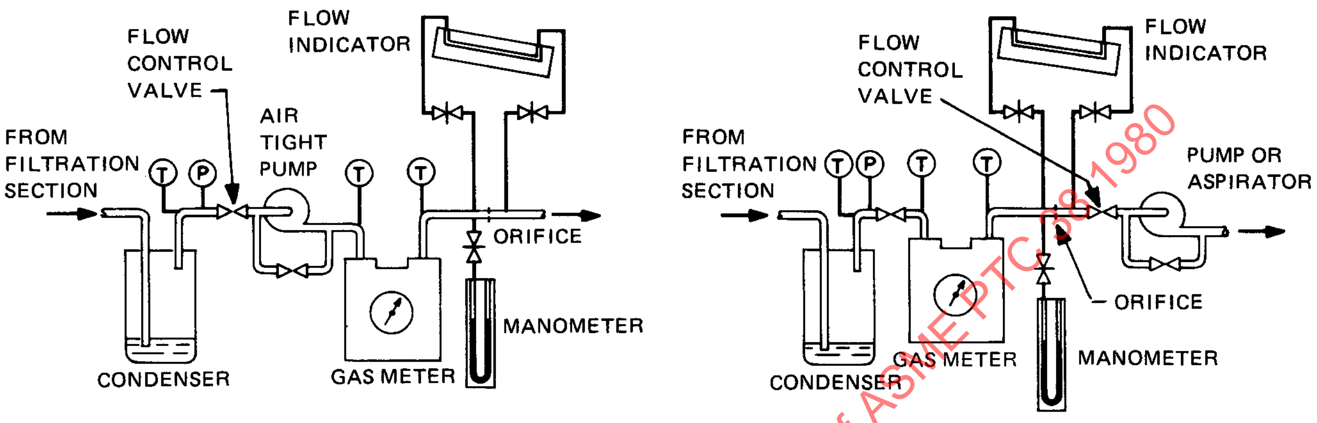
FIG. C-1 SAMPLE TRAIN CONFIGURATIONS – FILTRATION SECTION

Notes to Fig. C-1

1. In all of the above drawings "S"-Type (Stauscheibe) Pitot tubes are shown. However, Standard-Type Pitot tubes may be used instead. In either case, proper calibration is required as specified in this Code.

2. Pitot tubes are shown as integral parts of the Sample Train as continuous monitoring of gas velocity at the sampling point is usually required. If it can be established that the gas velocity at each sampling point does not vary by more than ± 10% during a test run and that point-to-point velocity gradients are not great, gas velocity data may be obtained by detached Pitot tube traverses made both before and after the run. However, this can be done only by agreement of all parties concerned.

3. The Type 3 configuration, when used for high volume sampling, may not require heaters for the probe and for the external filter assembly if sample gas temperature can be maintained above the dewpoint temperature through the filter.

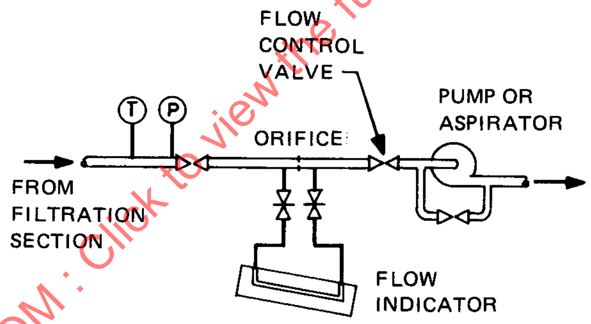


Alternate A

Gas Meter located after Pump

Alternate B

Gas Meter located before Pump



Alternate C

No Condenser and no Gas Meter

FIG. C-2 SAMPLE TRAIN CONFIGURATIONS – FLOW CONTROL SECTION

RECOMMENDED USE OF SAMPLING TRAINS FOR BASIC PROCESSES AND VARIOUS GAS CONDITIONS

Sampling of Particulate Matter Emissions

Sampling Train No.	PROCESS													
	Fossil Fuel			Cement			Iron & Steel					Incineration		Other
	Pulv. Coal	Stoker Coal	Oil	Wet Process	Dry Process	Coolers	BOF	Open Hearth	Sinter	Blast Furnace	Scarf.	Under 800° F	Over 800° F	
1.	X	X	X	X	X	X	X	X	X	X	X	X	–	Relate to Gas Conditions Below
2.	X	X	–	X	X	X	–	X	X	X	X	X	–	
3.	(1)	–	–	–	–	(1)	(1)	(1)	(1)	(1)	(1)	(1)	X	

Note: (1) Train No. 3 can be used when wet scrubbers exist.

Sampling Train No.	SPECIFIC GAS CONDITIONS										
	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	
	< 200° F < 5 % H_2O < 100 mg	200° F to 500° F < 10% H_2O < 100 mg	200° F to 500° F > 10% H_2O < 100 mg	400° F to 800° F 15-35% H_2O < 100 mg	500° F to 800° F 5-35% H_2O > 100 mg	Over 800° F	Saturated Moist Conditions	Very Low Ambient Temperature			
1.	X	X	X	X							
2.			X	X	X						
3.						X	X	X			

The Sampling Train Nos. indicated above refer to the "Sample Train Configurations – Filtration Section" shown in Fig. C-1.

FIG. C-3 SAMPLE TRAIN CONFIGURATIONS – SELECTION GUIDE

APPENDIX D

FILTRATION EFFICIENCY OF FILTERS FOR FINE PARTICULATE MATTER

In the absence of specific knowledge about the filtration efficiency of any particular filter medium it is tempting to draw inferences from data culled from the literature of fine particle technology. In reviewing such data it is important to restrict one's observations to those data that are based on weight determinations and weight efficiency of the filter media tested.

Two test methods, other than those based on weight, are common in the literature of fine particle technology, and they bear no relation to each other. These are the 0.3 micron DOP particle cloud method, evaluated by light scattering, and the dust spot method, evaluated by light transmission measurements.

Dust Spot

A great deal of the data on dust spot efficiencies appears in the literature dealing with air cleaning performance and "high efficiency" ventilation air cleaning equipment, i.e., some filters and especially two stage electric precipitators (Penney type, not Cottrell). Air cleaning efficiency of these devices is rated on the basis of "dust spot" measurements. This refers to the use of ambient air with its normal complement of fine particulate matter as the test stream. Samples of air entering the precipitator and from the cleaned air stream are simultaneously drawn through equal size circular areas of white filter paper at metered rates for a measured period of time. The opacities of resulting dark spots on the filter paper are measured by light transmission, the optical densities calculated and the two values compared.

The quantities of particulate matter represented by the optical density consist overwhelmingly of the particles smaller than 1-2 microns because these are the ones having the greatest opacity effect. The few largest particles exert a negligible effect on the opacity although they account dominantly for the weight of the mixture.

DOP

During the years since 1949, an immensely useful technique has been available and widely used in laboratory research, the generation of monodisperse clouds of dioctyl phthalate (DOP) aerosol and light scattering instrumentation for measurement of their concentration. They are characterized by a unique and uniform particle size, commonly 0.3 micron (0.25 to 0.35 microns) and in that respect are in marked contrast to industrial and other dust or aerosol clouds which are always composed of widely heterogeneous particle sizes.

Filtration Efficiency of Various Filter Media

Measurements of filter or precipitator performance using DOP aerosols do not represent, even approximately, the filtration efficiency of filters described on a *mass* basis, mainly because the *mass* fraction of 0.3 micron particles in industrial particle clouds is insignificantly small; they are overwhelmed by the presence of larger particles, including flocculated clusters of smaller particles which behave like larger particles.

In both of these two methods the fine particle fraction dominates the measurement whereas the large particle fraction dominates weight measurements. The different filtration efficiencies are illustrated in the following table, which shows filtering characteristics of several ventilation air filters. It is adapted from a tabulation in the ASHRAE Guide & Data Book, chapter on "Air Cleaners" (numbering varies annually). (See Reference [26].)

Table D-1 Filtration Efficiency of Various Filter Media

Efficiency rating of air filtering media depends on the test method employed, illustrated by the performance data below on several filters used in ventilation-air cleaning.

	Filtration efficiency based on		
	Mass	Dust Spot	0.3 micron DOP
Thin paper-like sheets (glass or cellulose fibers)	80-90%	20-35%	0.0%
Mats of 5-10 micron fibers, ¼-½ in. thick	90-95	40-60	15-25
Mats of 3-5 micron fibers, ¼-¾ in. thick	95	60-80	35-40
Mats of ½-2 micron glass fibers	NA*	90-98	75-90

*"Not Applicable." Close to 100%, therefore weight efficiency basis is impractical.

As emphasized elsewhere in this Code, other characteristics of the filter media must also be considered in the selection of the filter to be used in a particular test situation. As well as possessing adequate filtration efficiency, the filter must also be unaffected (chemically and physically) by the gas being sampled at the temperatures to be encountered. Furthermore, it must be inert in respect to its effect on the materials being filtered.

Filters are obtainable from a large number of vendors – in a wide range of materials and configurations. The full specifications of all filters (filter media and filter holder) should be studied carefully in the technical literature available from the vendors to insure suitability for purposes intended. The selection of the filter to be used should be a matter for mutual agreement of all parties to the test.

APPENDIX E

SAMPLING IN LOW VELOCITY GAS STREAMS

Sometimes duct arrangements may be encountered where the logical cross section for measurement of particulate matter concentrations is in streams where velocities are too low to be measured by recommended instruments – for example, discharge from a scrubber immediately into a low velocity tower or filtered gas discharge from a pressure-type bag filter dust collector without a stack.

The best remedy in such a situation would be the addition of a duct through which gas would be channeled at measurable velocities. Such additional flues need not necessarily accomodate the total gas flow.

Where this procedure is impractical, the total gas flow may be determined at another section of the system where the velocities are high enough to be measured; and from this determination of total gas flow and the cross-sectional area in the low velocity section, one calculates the average velocity over the total low velocity flow area.

Sampling in the low velocity flow area is then conducted at a constant flow rate determined by the calculated average velocity obtained while traversing the area at the required number of points defined according to the conventional procedures.

The consequences of this sampling procedure, as to potential error, result from the fact that at some points, sampling will be lower and at other points will be greater, than isokinetic rates. If the variation in velocity is judged not excessive, the resulting average concentration may be acceptably accurate, especially where the particulate matter is free of large particles.

APPENDIX F

PARTICULATE MATTER COLLECTION AND THE EFFECT OF CONDENSED SO_3

The greater part of the sulfur released from fuel during combustion processes appears in the product of combustion as SO_2 which passes unaffected as a gas through particulate sampling equipment. However, a small percentage is oxidized to SO_3 which in cooler flue gas, reacts with vapor phase water to form sulfuric acid.

If the gas temperature in the sampling probe falls below the dew point, the sulfuric acid may condense and increase the quantity of particulate matter collected. This increase may occur by reaction of the sulfuric acid with fly ash particles or with the sampling equipment to form additional solid compounds or by condensation followed by agglomeration of fly ash particles.

It follows that by maintaining the metal and gas temperatures of the sampling equipment above the acid dew point the above problems will be eliminated thus avoiding a positive error in the determination of particulate matter loadings.

Acid dew point is defined as the temperature at which the combustion gases are saturated with sulfuric acid and the dew point to sulfuric acid concentration relationship was determined using the condensation sampling method. In a special laboratory apparatus (Fig. F-1) known quantities of sulfuric acid were added to both air and flue gas streams and then collected in a specially designed condenser maintained at a temperature between the acid dew point and the water dew point. Sulfuric acid was thus condensed while all other flue-gas constituents remained in the flue gas (see Table F-1).

The agreement of dew point determination of this type with thermodynamically calculated data is shown in Fig. F-2.

TABLE F-1 EXPERIMENTAL RESULTS – AIR VS. SYNTHETIC FLUE GAS

Gas Composition	Volume, Liters	H_2SO_4, Added	ppm Recovered	Difference
Air	56.1	30.2	30.5	+ 0.3
Air	55.7	24.6	24.2	- 0.4
Air	55.7	26.9	26.7	- 0.2
Air	55.9	24.1	23.3	- 0.8
Air	55.9	28.2	27.6	- 0.6
Air	55.9	10.7	10.7	- 0.0
			Avg. Diff.	- 0.3
Sfg (1)	56.1	28.7	28.5	- 0.2
Sfg (1)	55.7	29.4	28.9	- 0.5
Sfg (1)	55.9	29.1	28.5	- 0.6
Sfg (1)	55.9	28.2	28.3	+ 0.1
Sfg (1)	55.7	27.6	27.2	- 0.4
Sfg (2)	55.7	27.7	27.4	- 0.3
Sfg (3)	55.7	28.6	28.2	- 0.4
Sfg (2)	55.9	10.5	10.3	- 0.2
			Avg. Diff.	- 0.3

---

(1) Synthetic flue gas containing approximately 2000 ppm sulfur dioxide.

(2) Synthetic flue gas containing approximately 750 ppm sulfur dioxide.

(3) Synthetic flue gas containing approximately 150 ppm sulfur dioxide.

Note: See References [18] through [24] in Section 7.

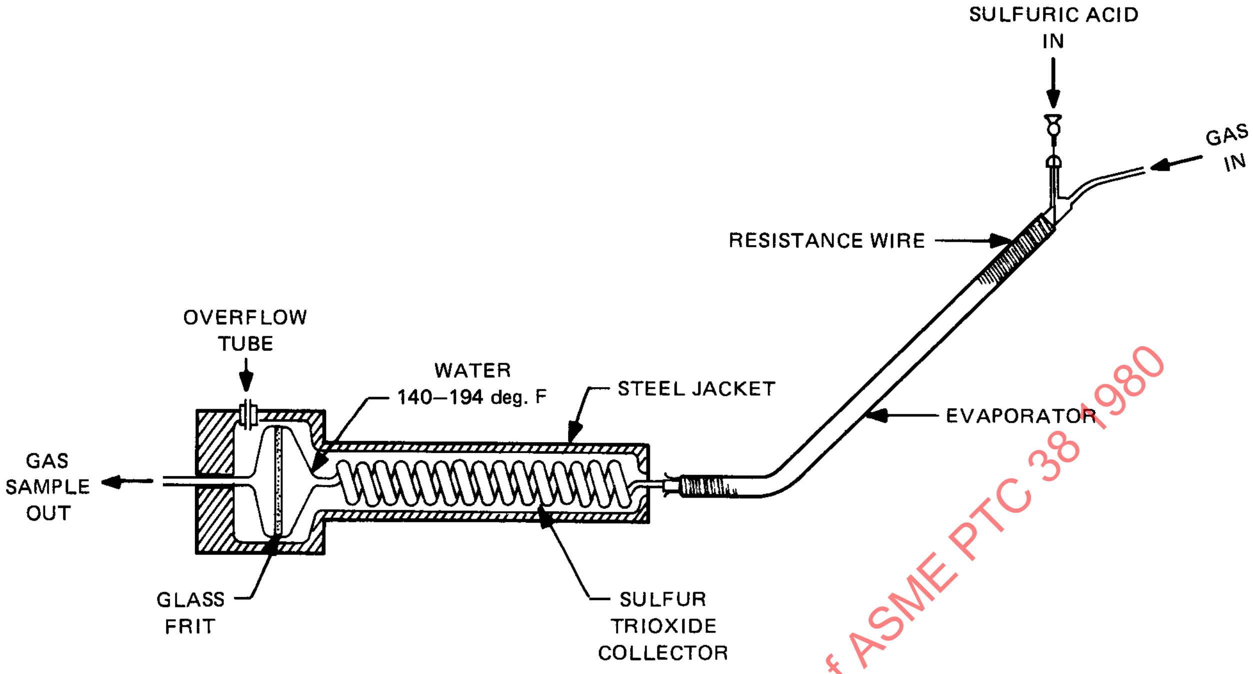


FIG. F-1 CALIBRATING APPARATUS FOR SULFUR TRIOXIDE COLLECTOR

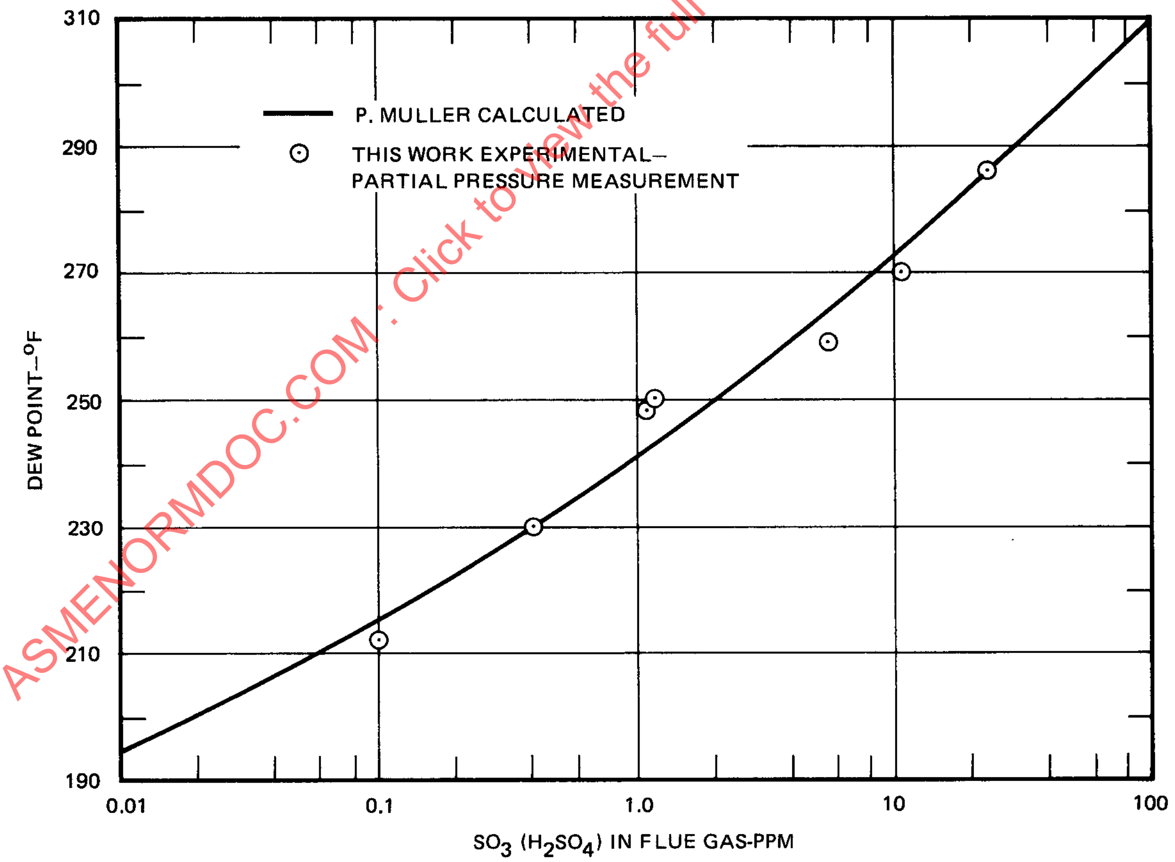


FIG. F-2 DEW POINT AS A FUNCTION OF H_2SO_4 CONCENTRATION

APPENDIX G

TYPICAL GAS VELOCITY AND PARTICULATE MATTER CONCENTRATION PROFILES

As indicated in this Code, gas velocity and particulate matter concentration can vary greatly between various points in a cross section of a duct. This situation is greatly aggravated by bends and restrictions in the gas flow path. Unfortunately, this situation occurs frequently in field tests of actual equipment.

Two sets of diagrams are included here to illustrate this situation.

The first set illustrates the nature and magnitude of the variation of gas flow velocity and the rate of transport of particulate matter (product of gas flow rate and particulate matter concentration) at various points in cross sections of typical duct and stack configurations.

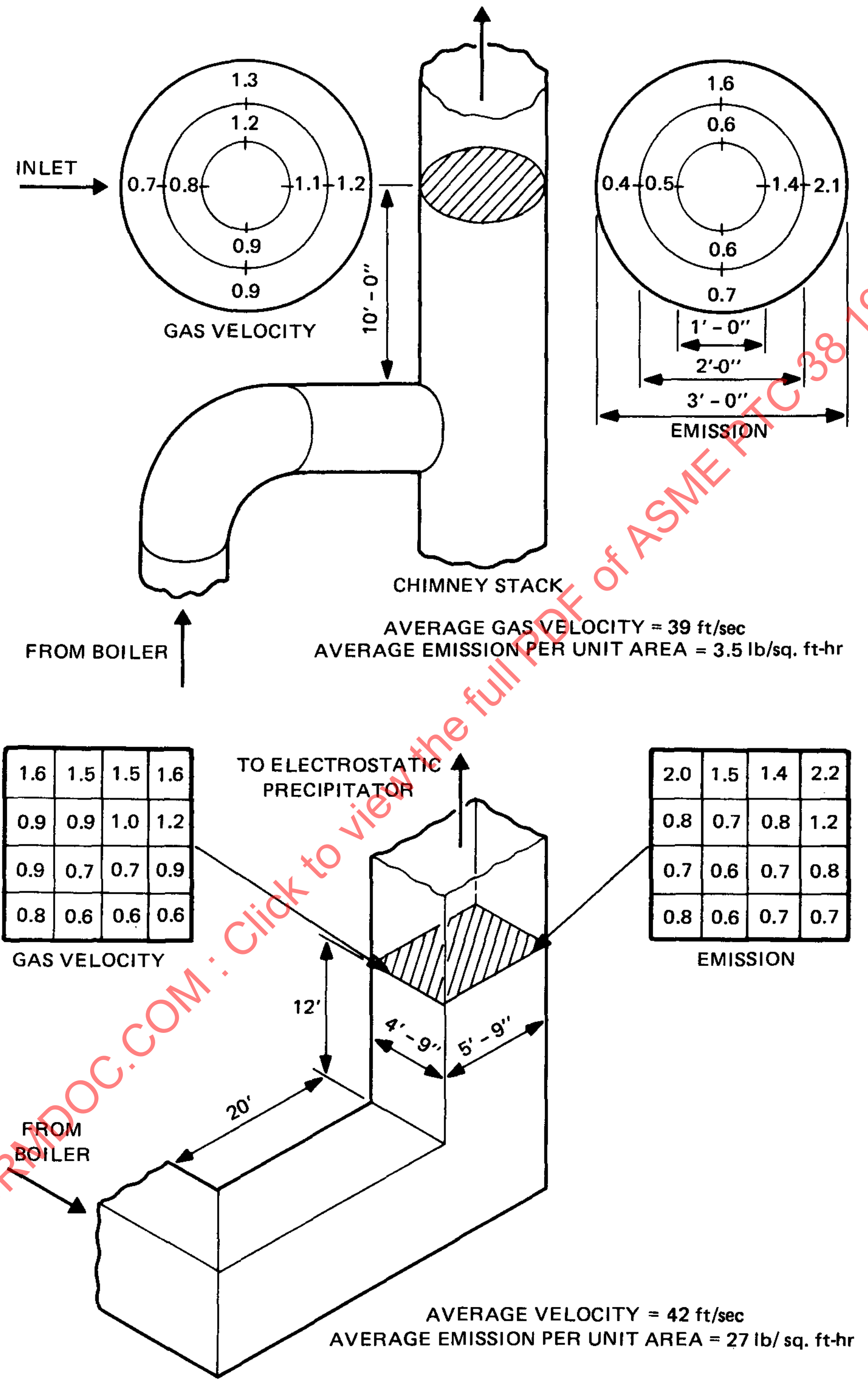
The second set shows gas velocity distribution profiles obtained during actual field tests on large steam generating units. Total gas flow rates, computed by three different procedures, are shown for each example. The procedures used were:

(a) Conventional gas flow rate calculation procedure using Pitot tube gas velocity data applied to "equal areas" for each test point.

(b) Stoichiometric gas flow rate calculation, based upon chemical analyses of the fuel burned and of the gases in the duct passing the test points.

(c) Modified gas flow rate calculation procedure using Pitot tube gas velocity data. In this procedure, isobaric lines were drawn on a cross section diagram of the duct – their locations determined from Pitot tube data which had previously been plotted thereon. Total gas flow rates were then calculated by summing up the products of the areas between the isobars and the estimated average gas velocity in each such area – the size of the areas determined by means of a planimeter measurement of each of the cross section drawings.

The differences between the gas flow rates, as calculated by these three procedures, illustrate the inherent difficulty of obtaining accurate gas flow rate test data from Pitot tube velocity traverses under the frequently prevailing adverse flow conditions prevailing in typical flue gas ducts.



AVERAGE GAS VELOCITY = 39 ft/sec
AVERAGE EMISSION PER UNIT AREA = 3.5 lb/sq. ft-hr

1.6	1.5	1.5	1.6
0.9	0.9	1.0	1.2
0.9	0.7	0.7	0.9
0.8	0.6	0.6	0.6

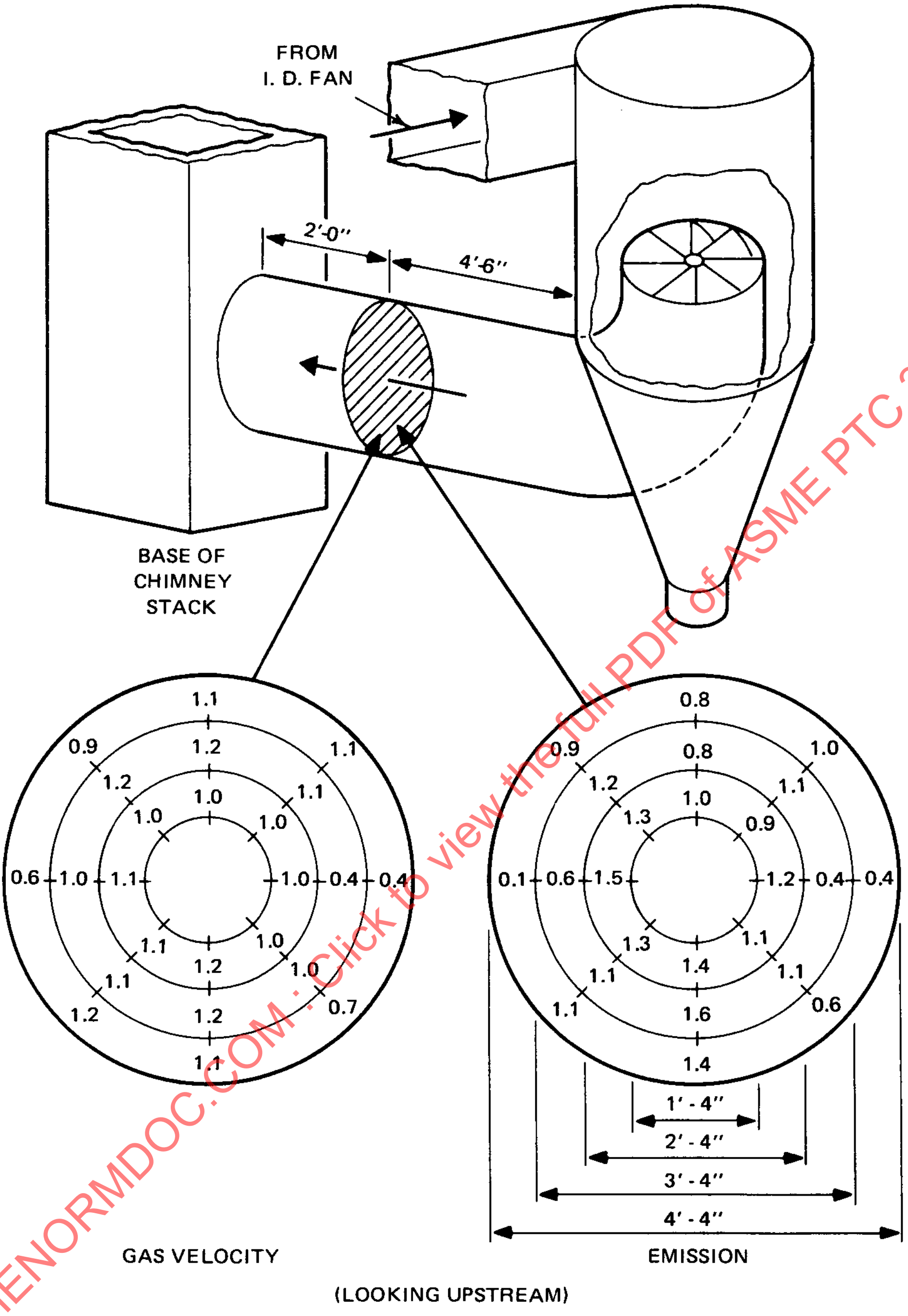
GAS VELOCITY

2.0	1.5	1.4	2.2
0.8	0.7	0.8	1.2
0.7	0.6	0.7	0.8
0.8	0.6	0.7	0.7

EMISSION

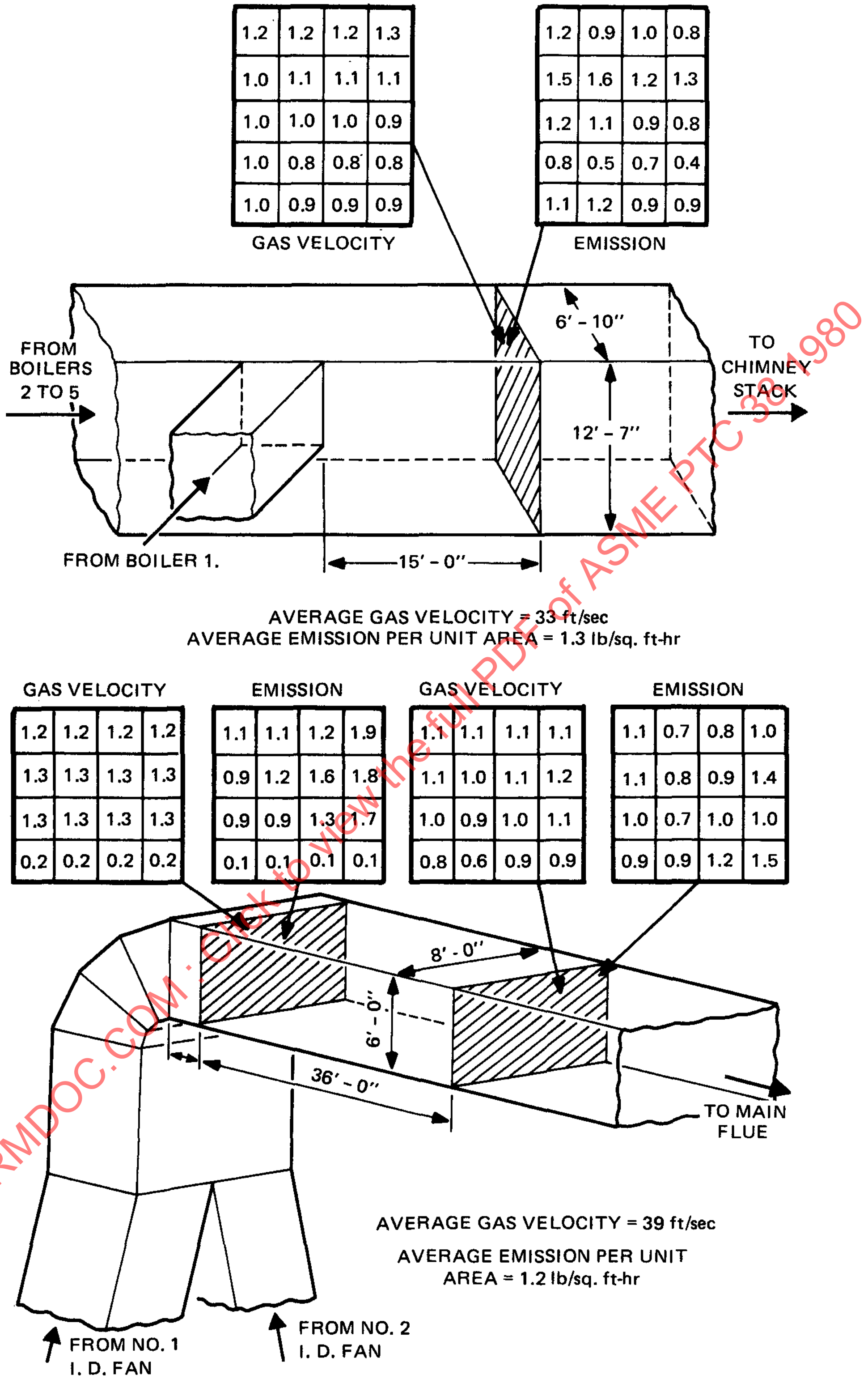
AVERAGE VELOCITY = 42 ft/sec
AVERAGE EMISSION PER UNIT AREA = 27 lb/ sq. ft-hr

FIG. G-1 GAS FLOW VELOCITY AND THE RATE OF TRANSPORT OF PARTICULATE MATTER



AVERAGE GAS VELOCITY = 43 ft sec
AVERAGE EMISSION PER UNIT AREA = 3.0 lb/sq. ft-hr

FIG. G-1 (Cont'd)



GAS VELOCITY

1.2	1.2	1.2	1.3
1.0	1.1	1.1	1.1
1.0	1.0	1.0	0.9
1.0	0.8	0.8	0.8
1.0	0.9	0.9	0.9

EMISSION

1.2	0.9	1.0	0.8
1.5	1.6	1.2	1.3
1.2	1.1	0.9	0.8
0.8	0.5	0.7	0.4
1.1	1.2	0.9	0.9

AVERAGE GAS VELOCITY = 33 ft/sec
AVERAGE EMISSION PER UNIT AREA = 1.3 lb/sq. ft-hr

GAS VELOCITY

1.2	1.2	1.2	1.2
1.3	1.3	1.3	1.3
1.3	1.3	1.3	1.3
0.2	0.2	0.2	0.2

EMISSION

1.1	1.1	1.2	1.9
0.9	1.2	1.6	1.8
0.9	0.9	1.3	1.7
0.1	0.1	0.1	0.1

GAS VELOCITY

1.1	1.1	1.1	1.1
1.1	1.0	1.1	1.2
1.0	0.9	1.0	1.1
0.8	0.6	0.9	0.9

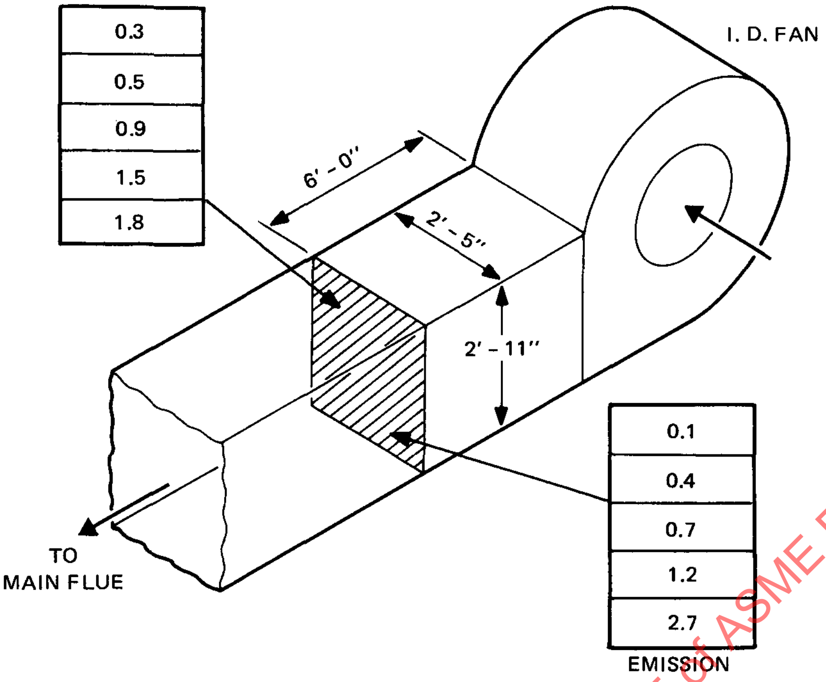
EMISSION

1.1	0.7	0.8	1.0
1.1	0.8	0.9	1.4
1.0	0.7	1.0	1.0
0.9	0.9	1.2	1.5

AVERAGE GAS VELOCITY = 39 ft/sec

AVERAGE EMISSION PER UNIT AREA = 1.2 lb/sq. ft-hr

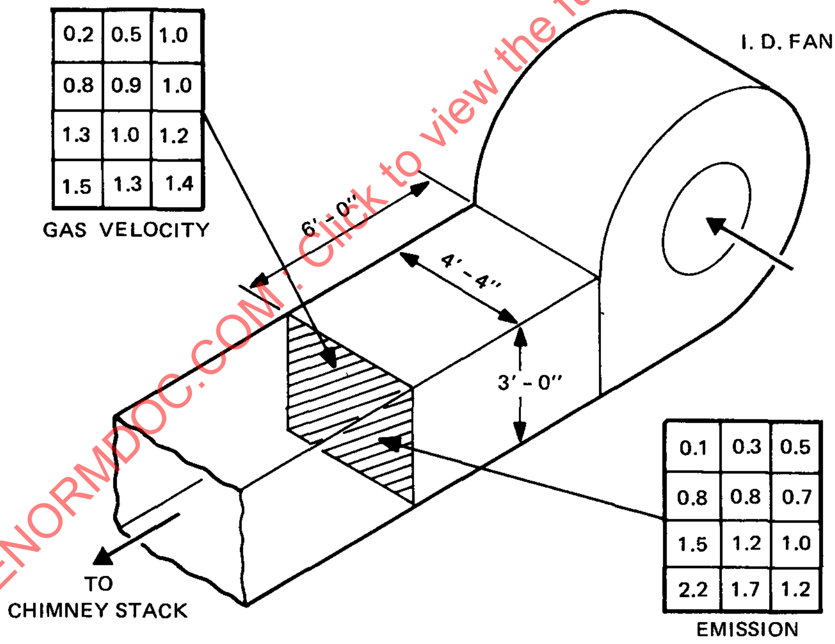
FIG. G-1 (Cont'd)



0.3
0.5
0.9
1.5
1.8

EMISSION
0.1
0.4
0.7
1.2
2.7

AVERAGE GAS VELOCITY = 110 ft/sec
AVERAGE EMISSION PER UNIT AREA = 18.3 lb/sq.ft-hr



GAS VELOCITY

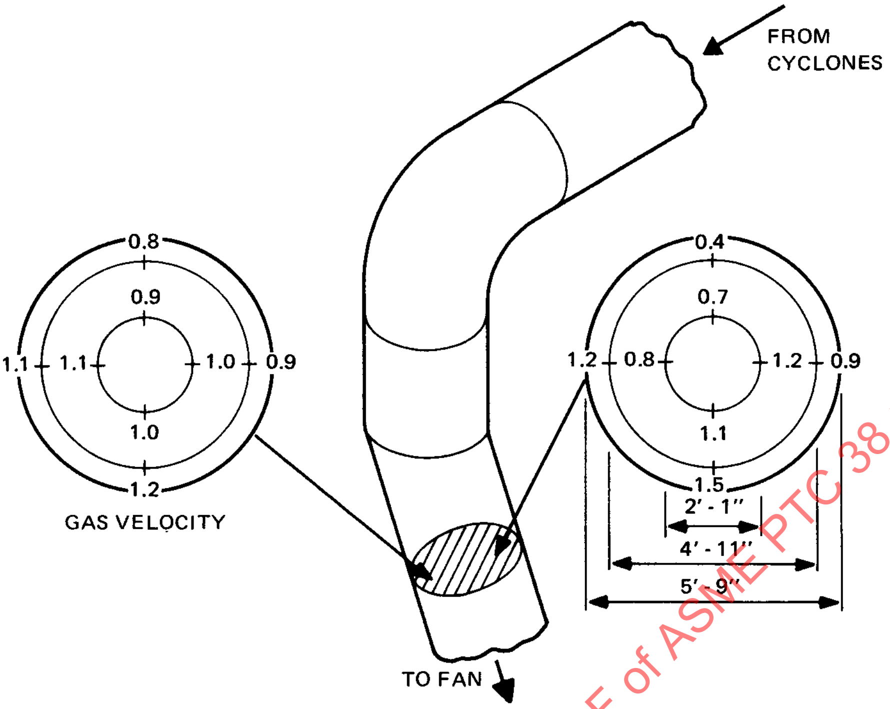
0.2	0.5	1.0
0.8	0.9	1.0
1.3	1.0	1.2
1.5	1.3	1.4

EMISSION

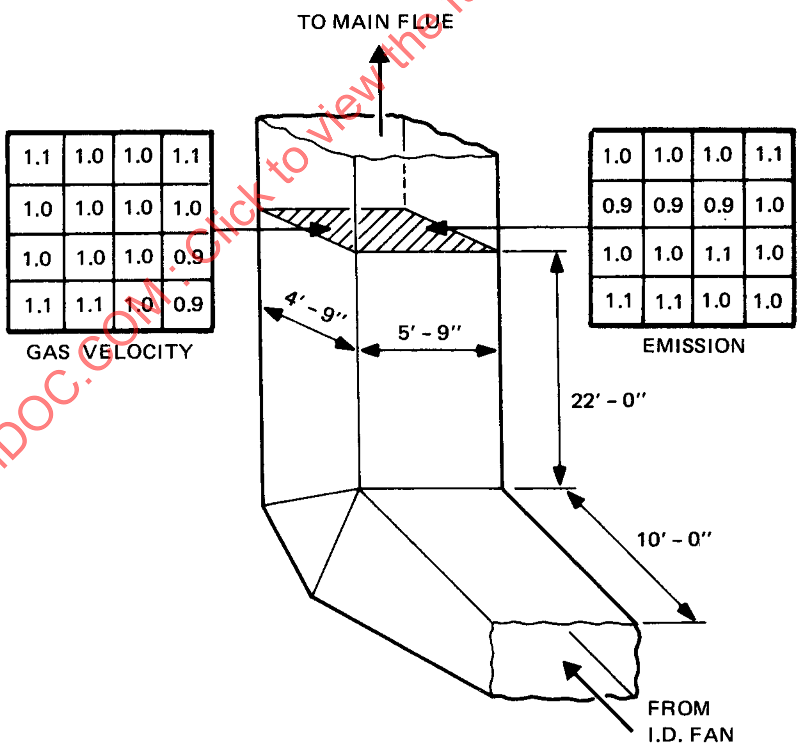
0.1	0.3	0.5
0.8	0.8	0.7
1.5	1.2	1.0
2.2	1.7	1.2

AVERAGE GAS VELOCITY = 43 ft/sec
AVERAGE EMISSION PER UNIT AREA = 3.0 lb/sq. ft-hr

FIG. G-2



AVERAGE GAS VELOCITY = 45 ft./sec
AVERAGE EMISSION PER UNIT AREA = 4.6 lb/sq. ft-hr



1.1	1.0	1.0	1.1
1.0	1.0	1.0	1.0
1.0	1.0	1.0	0.9
1.1	1.1	1.0	0.9

GAS VELOCITY

1.0	1.0	1.0	1.1
0.9	0.9	0.9	1.0
1.0	1.0	1.1	1.0
1.1	1.1	1.0	1.0

EMISSION

AVERAGE GAS VELOCITY = 52 ft/sec
AVERAGE EMISSION PER UNIT AREA = 2.2 lb/sq. ft-hr

FIG. G-2 (Cont'd)

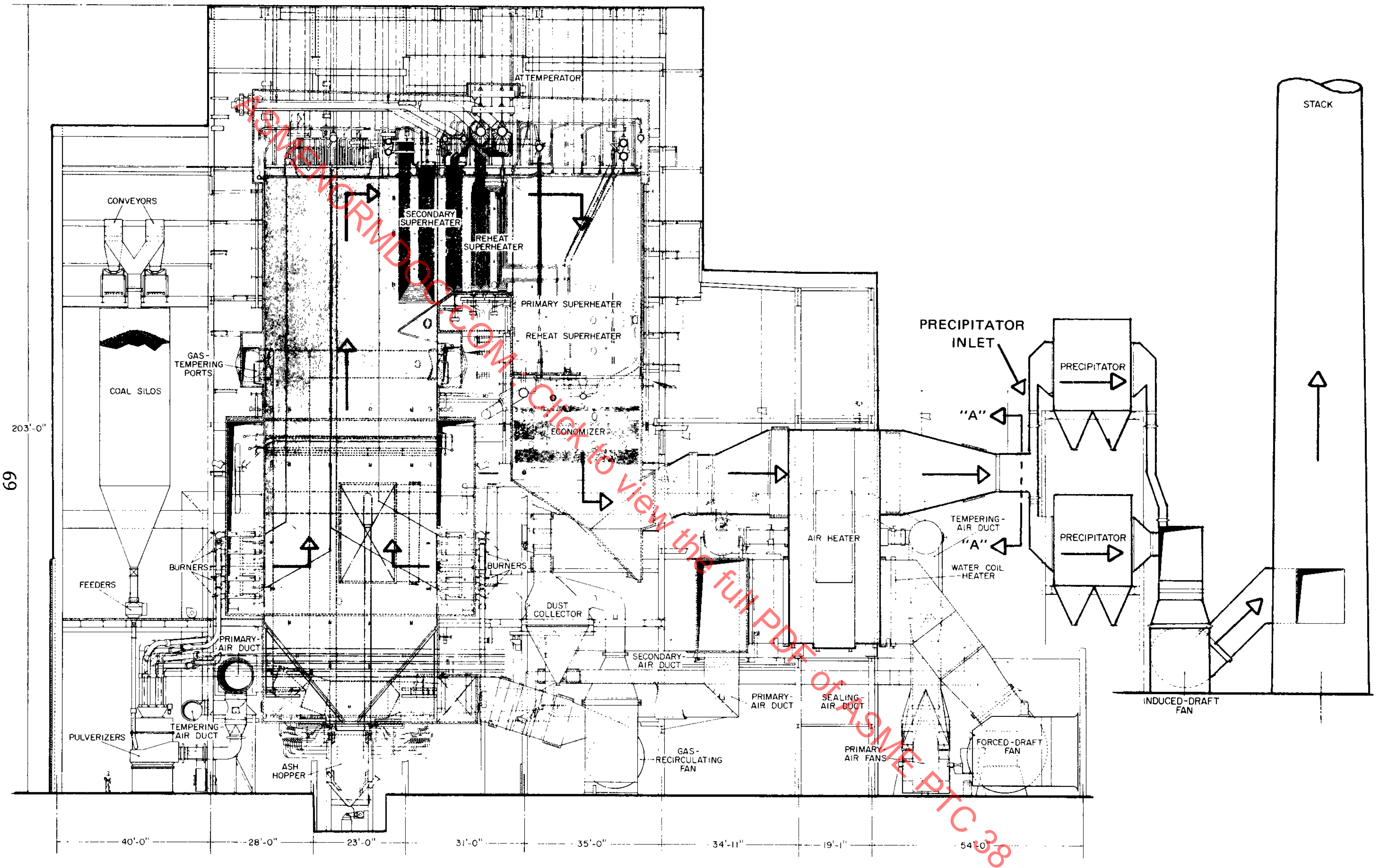
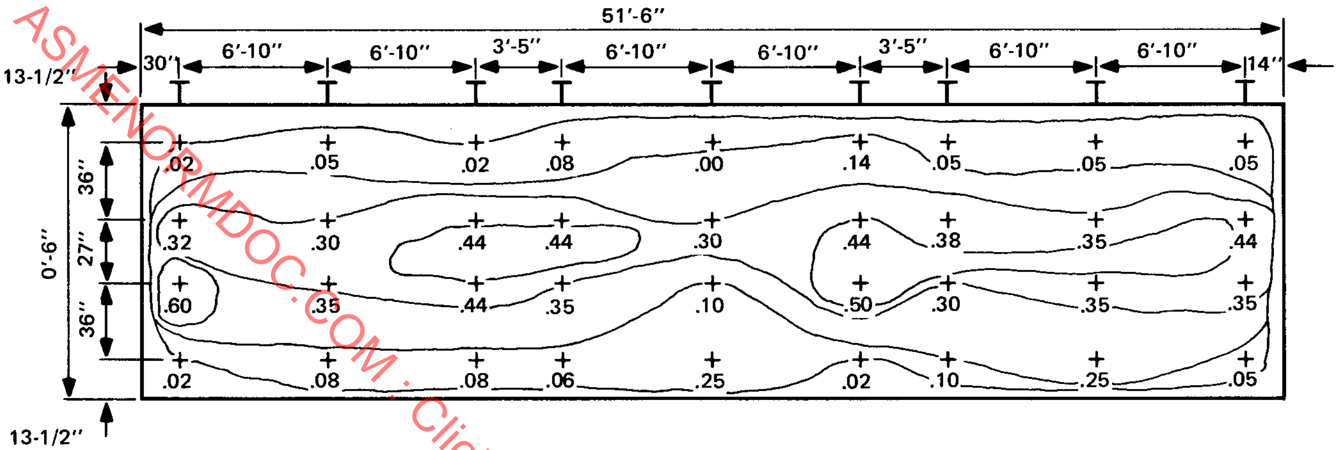
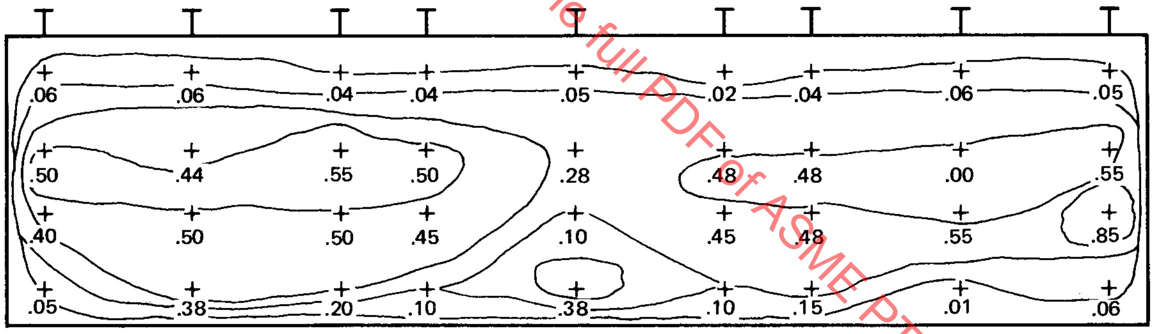


FIG. G-3 GAS VELOCITY DISTRIBUTION PROFILES UNDER ACTUAL TEST CONDITIONS



North Precipitator Inlet

ACFM by velocity head	1,119,353
ACFM from fuel and gas analysis	1,078,256
ACFM by velocity head (area weighted)	1,064,513



SECTION A-A

South Precipitator Inlet

ACFM by velocity head	1,204,250
ACFM from fuel and gas analysis	1,072,307
ACFM by velocity head (area weighted)	1,104,925

FIG. G-3 (Cont'd)

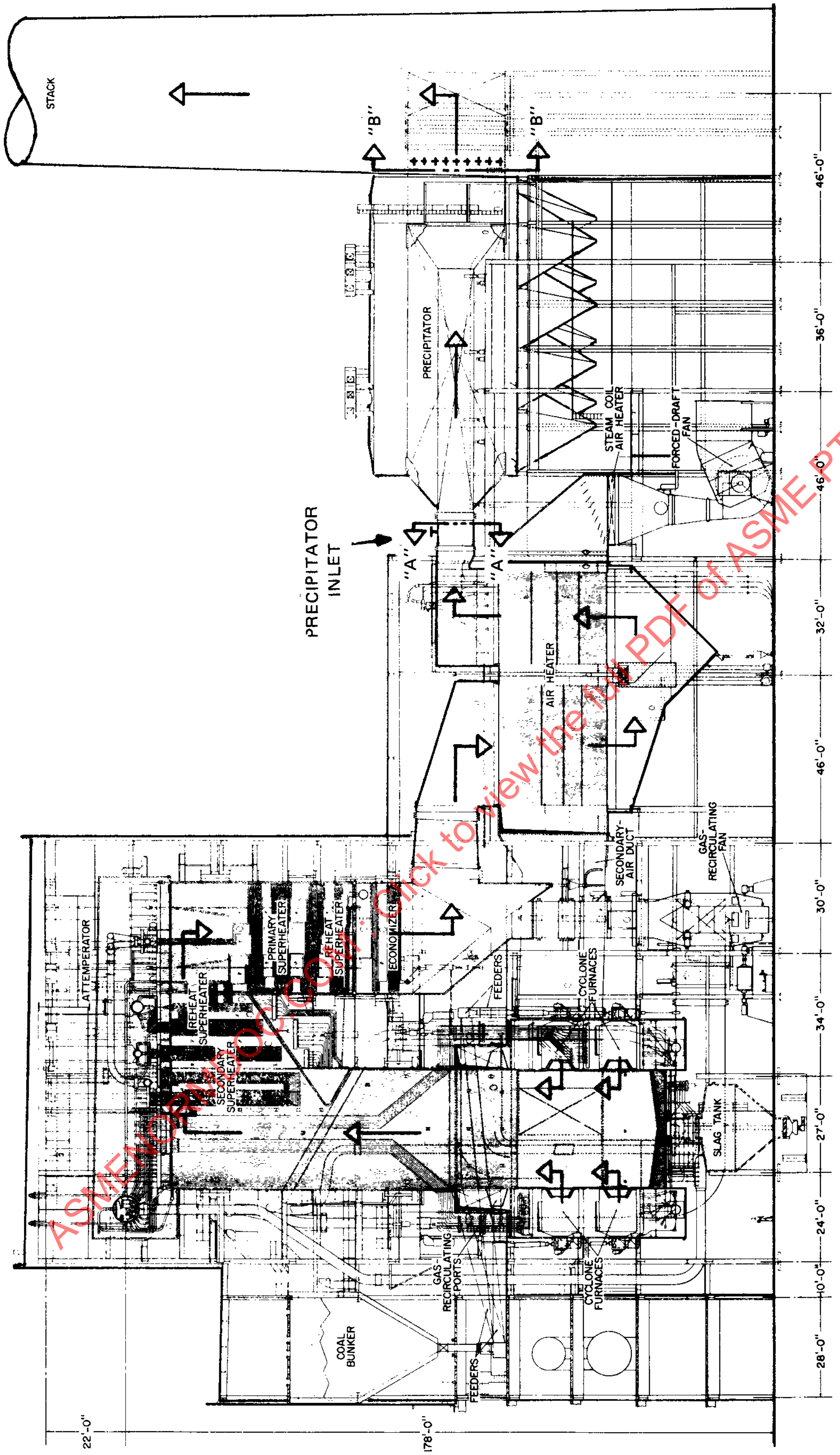
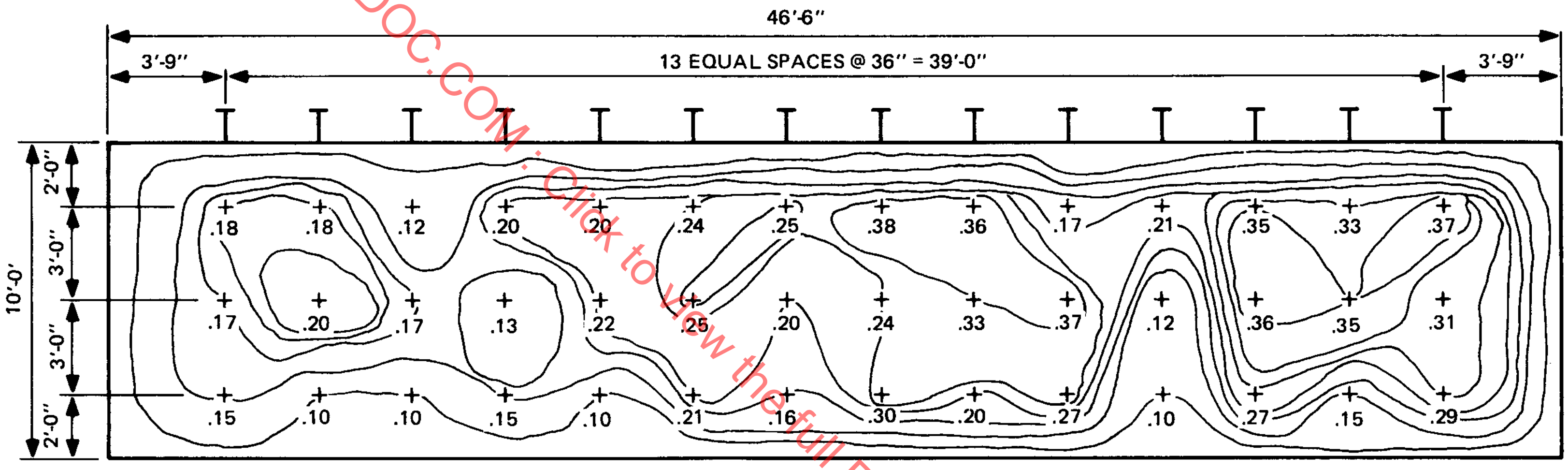

STACK
"B"
"B"
PRECIPITATOR
STEAM COIL AIR HEATER
FORCED-DRAFT FAN
PRECIPITATOR INLET
"A"
"A"
AIR HEATER
SECONDARY-AIR DUCT
GAS-RECIRCULATING FAN
ATTEMPERATOR
REHEAT SUPERHEATER
PRIMARY SUPERHEATER
REHEAT SUPERHEATER
SECONDARY SUPERHEATER
ECONOMIZER
FEEDERS
CYCLONE FURNACES
SLAG TANK
GAS-RECIRCULATING PORTS
CYCLONE FURNACES
COAL BUNKER
FEEDERS
46'-0"
36'-0"
46'-0"
32'-0"
46'-0"
30'-0"
34'-0"
27'-0"
24'-0"
10'-0"
28'-0"
22'-0"
178'-0"

FIG. G-4



SECTION A-A

South Precipitator Inlet

ACFM by velocity head	996,030
ACFM from fuel and gas analysis	840,617
ACFM by velocity head (area weighted)	844,000

FIG. G-4 (Cont'd)

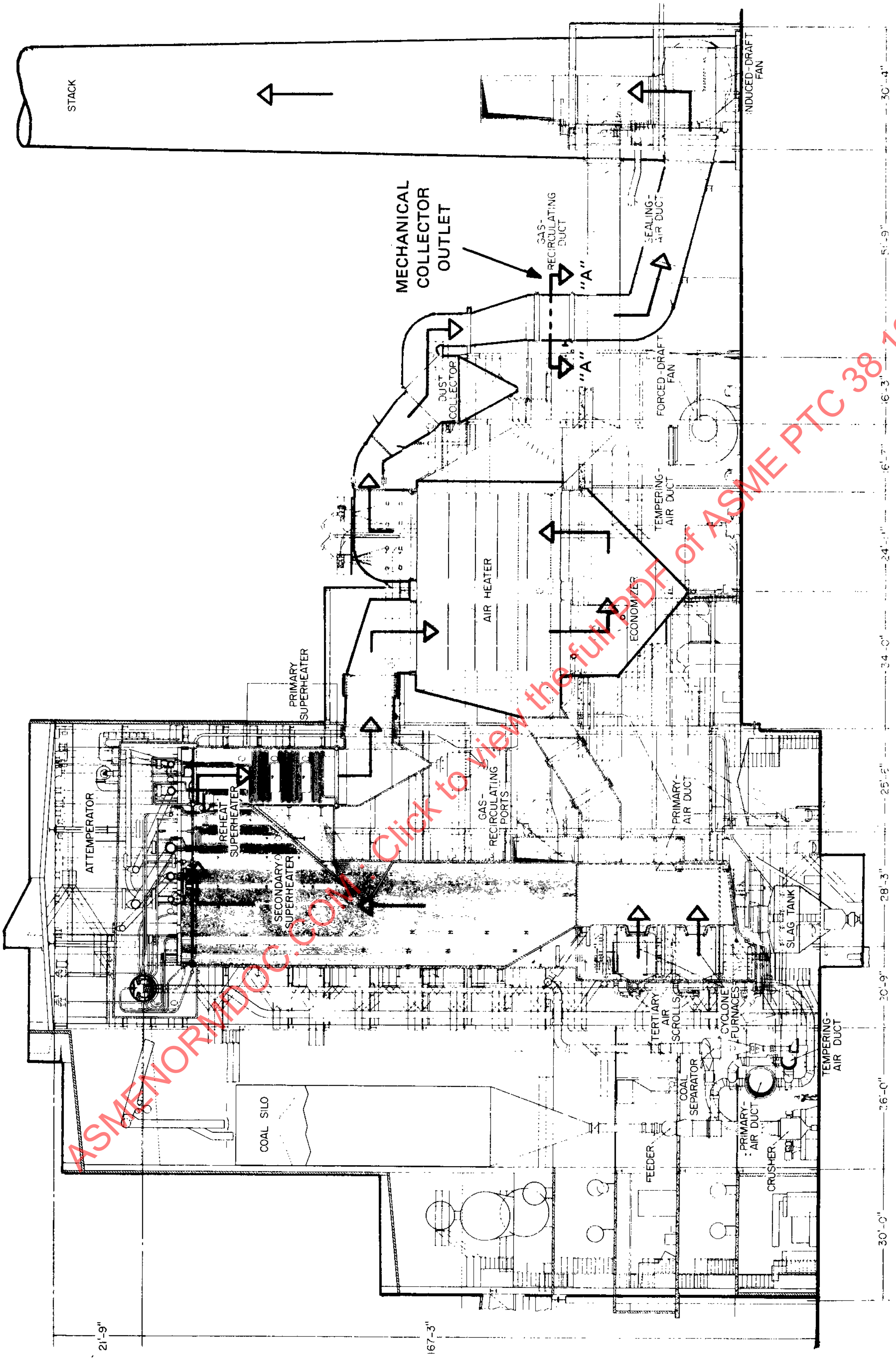
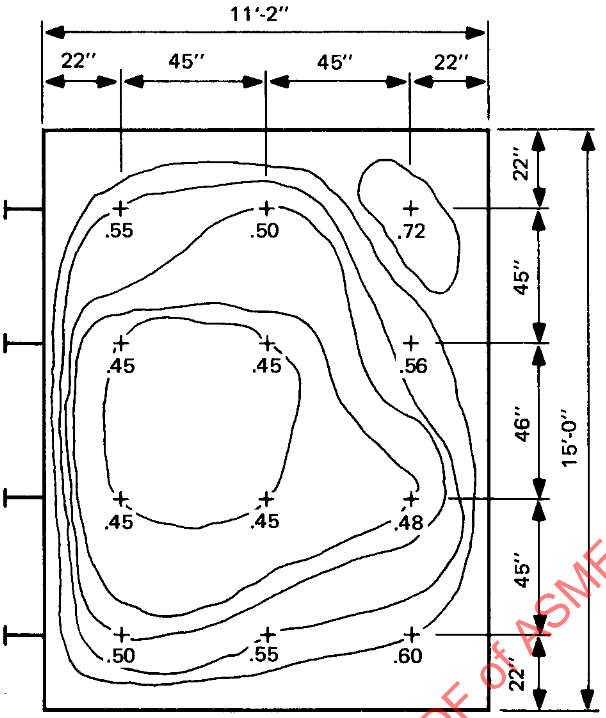
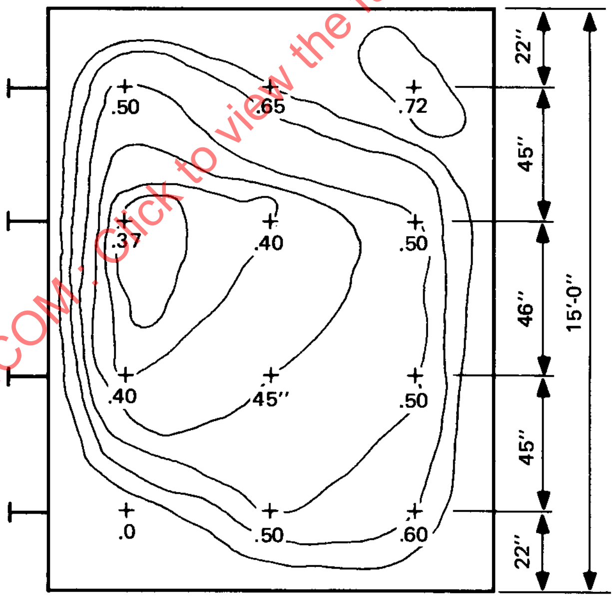

STACK
INDUCED-DRAFT FAN
MECHANICAL COLLECTOR OUTLET
GAS-RECIRCULATING DUCT
SEALING-AIR DUCT
"A"
"A"
DUST COLLECTOR
FORCED-DRAFT FAN
TEMPERING-AIR DUCT
AIR HEATER
ECONOMIZER
PRIMARY SUPERHEATER
ATTEMPERATOR
REHEAT SUPERHEATER
SECONDARY SUPERHEATER
GAS-RECIRCULATING PORTS
PRIMARY-AIR DUCT
SLAG TANK
TERTIARY AIR SCROLLS
CYCLONE FURNACES
TEMPERING-AIR DUCT
COAL SEPARATOR
PRIMARY-AIR DUCT
COAL SILO
FEEDER
CRUSHER
30'-4"
51'-9"
16'-3"
16'-7"
24'-1"
34'-0"
25'-6"
28'-3"
30'-9"
36'-0"
30'-0"
21'-9"
167'-3"

FIG. G-5



LEFT FLUE



RIGHT FLUE

Mechanical Collector Outlet

ACFM by velocity head	1,185,604
ACFM from fuel and gas analysis	1,015,667
ACFM by velocity head (area weighted)	1,090,852

FIG. G-5 (Cont'd)

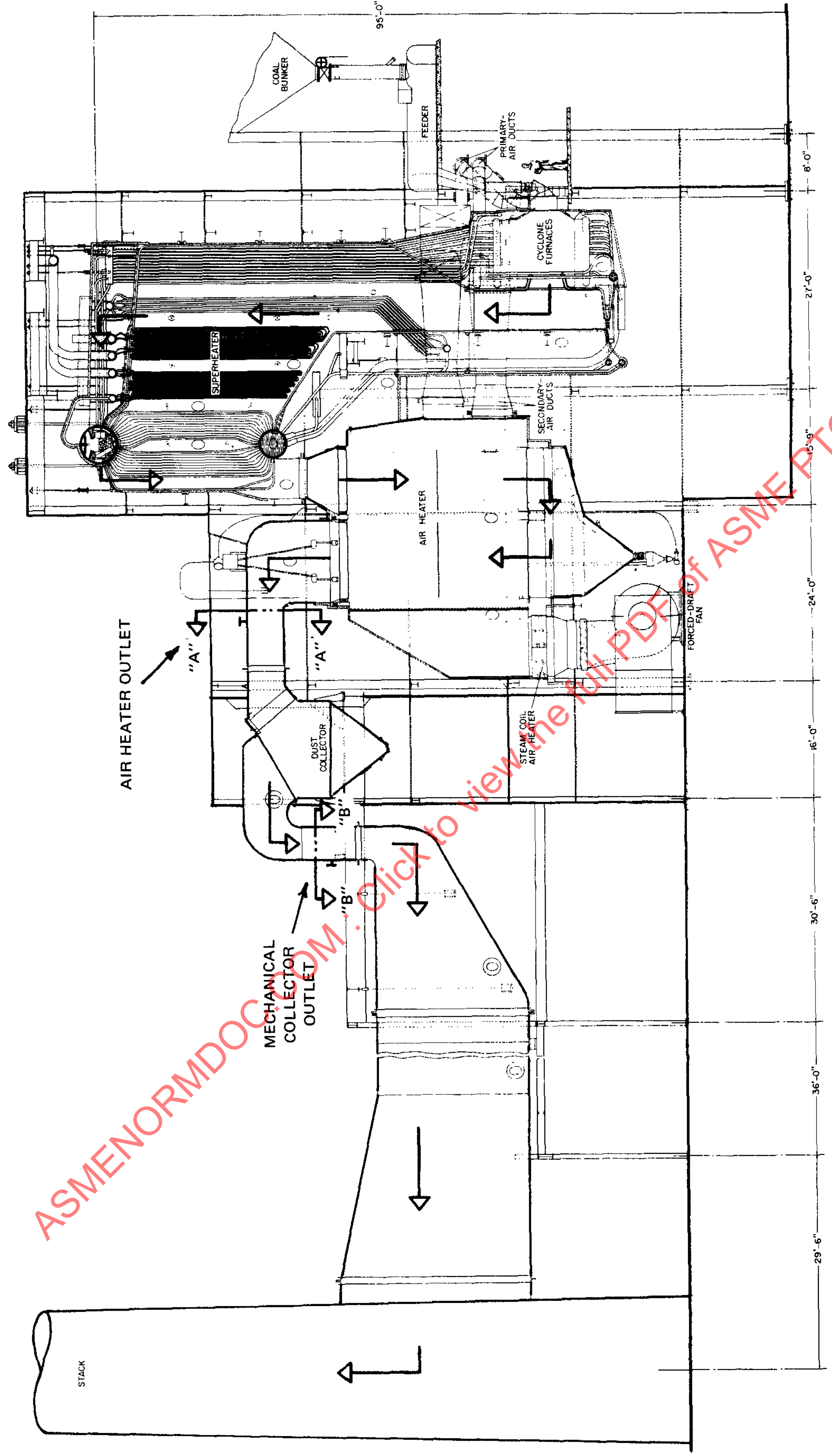
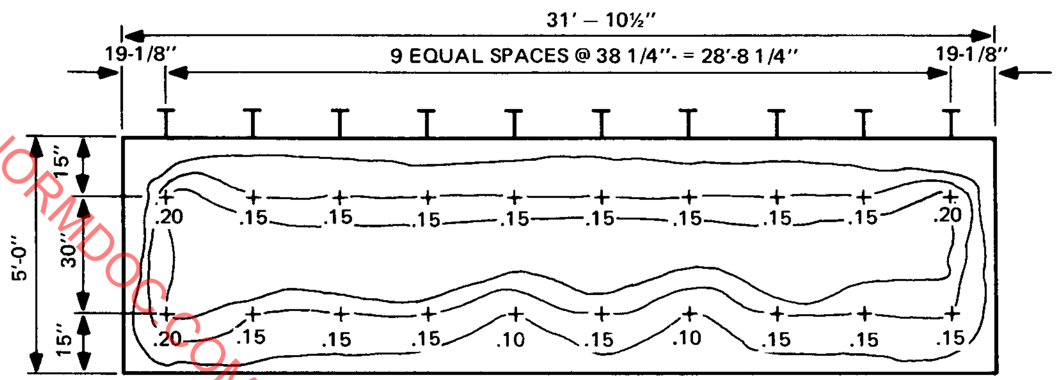

95'-0"
COAL BUNKER
FEEDER
PRIMARY-AIR DUCTS
CYCLONE FURNACES
SUPERHEATER
SECONDARY-AIR DUCTS
AIR HEATER
FORCED-DRAFT FAN
STEAM COIL AIR HEATER
DUST COLLECTOR
AIR HEATER OUTLET
"A"
"A"
"B"
"B"
MECHANICAL COLLECTOR OUTLET
STACK
8'-0"
27'-0"
15'-9"
24'-0"
16'-0"
30'-6"
36'-0"
29'-6"

FIG. G-6

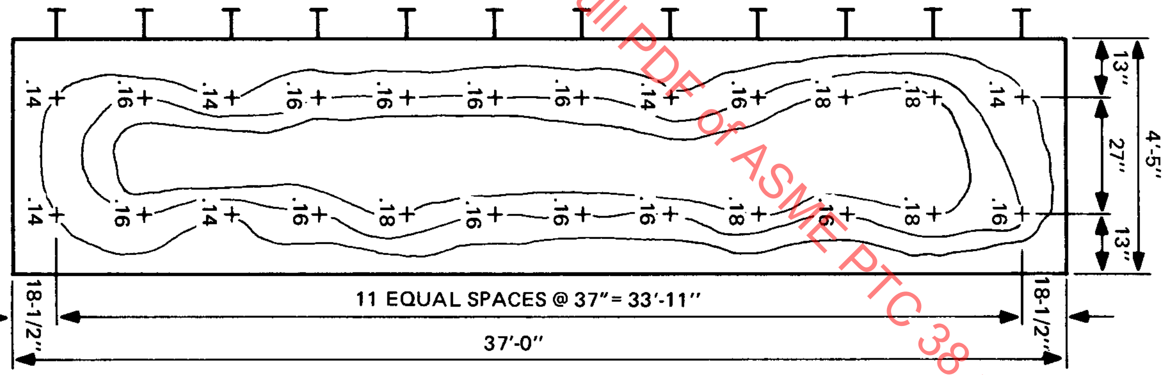


SECTION A–A

Air Heater Outlet

ACFM by velocity head	292,940
ACFM from fuel and gas analysis	241,900
ACFM by velocity head (area weighted)	239,783

SECTION B–B



Mechanical Collector Outlet

ACFM by velocity head	289,080
ACFM from fuel and gas analysis	241,900
ACFM by velocity head (area weighted)	242,480

FIG. G-6 (Cont'd)

APPENDIX H

METHODS FOR DETERMINING NUMBER AND LOCATION OF SAMPLING AREAS

The number and location of sampling points required to obtain valid average gas flow data and representative samples of the particulate matter in the gas stream varies with the conditions at the test site.

In general, when the sampling cross section is located at least 8 equivalent diameters downstream and 2 diameters upstream of any flow disturbance, 12 sample points should be adequate. Figure H-1 is a guide for determining the number of sample points required when sampling large ducts and when the sampling cross section is located closer to upstream and/or downstream flow disturbances. For smaller ducts, a lesser number of sample points may be used, but in no case should less than 4 sample points be used for ducts having a diameter of 2 ft or less. Exploratory Pitot tube traverses, to determine velocity distribution, will indicate if more or less sample points are required to obtain representative sampling data.

Figure H-2 provides guidance for dividing a rectangular or circular duct into equal sampling areas or zones wherein the gas velocity and the particulate matter concentration determined by sampling at the center of each area shall be considered the average conditions prevailing for the area. The number of sampling points, or sampling areas, to be used in laying out the sampling area profile is determined as above.

In certain special cases, it may be necessary or desirable to deviate from the above criteria. This should only be done after attainment of sufficient data for the situation involved in respect to velocity and particulate matter concentration profiles to justify such action. If such action can then be fully justified, the tests may be conducted with the full approval of all the parties concerned. The background for such action, along with complete back-up data, should be fully discussed in the test report.

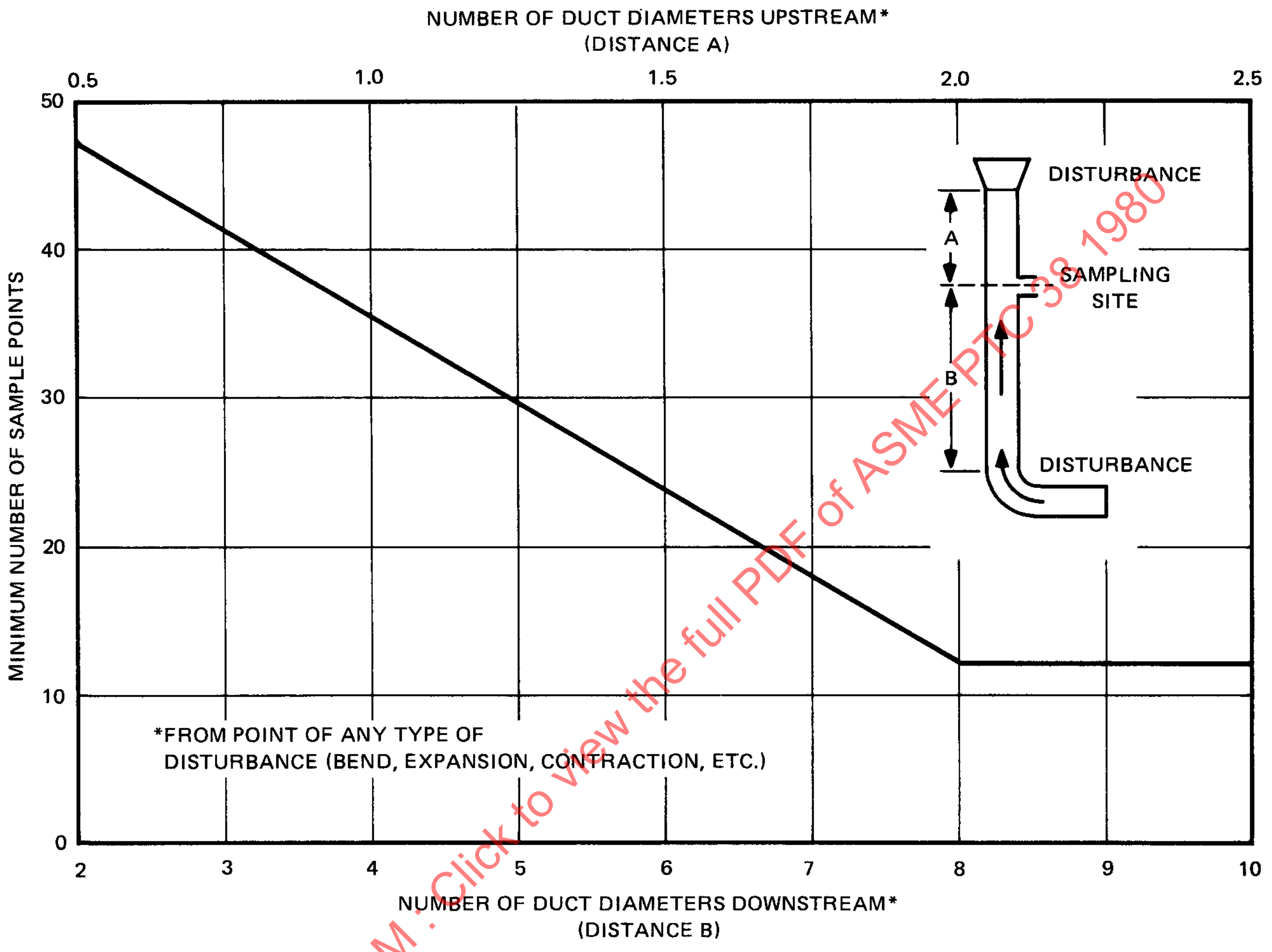
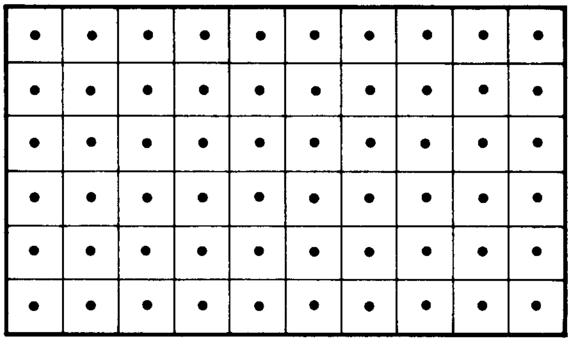
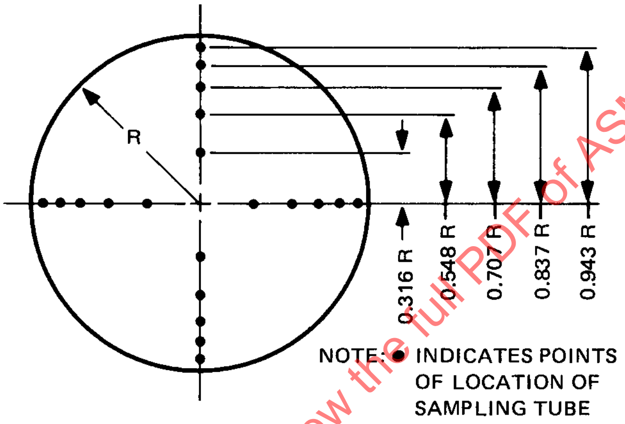


FIG. H-1 METHOD FOR DETERMINING THE NUMBER OF SAMPLE POINTS



A-CROSS SECTION OF RECTANGULAR DUCT



NOTE: ● INDICATES POINTS OF LOCATION OF SAMPLING TUBE

B-CROSS SECTION OF CIRCULAR DUCT
(USE OF 20 SAMPLING POINTS ILLUSTRATED)

Formula for determining location points in circular duct

$$r_p = \sqrt{\frac{2R^2(2p-1)}{n}}$$

where r_p = distance from center of duct to point p
R = radius of duct
p = sampling point number. To be numbered from center of duct outward. All four points on same circumference have same number.
n = total number of points

Note: r_p will be in same units as R.

Example: Duct radius = R; 20 points total.
Distance to point 3 = r_3.

$$r_3 = \sqrt{\frac{2R^2(2\cdot 3\ -1)}{n}} = \sqrt{\frac{2R^2 5}{20}} = \sqrt{.5R^2}$$

$$r_3 = 0.707R$$

FIG. H-2 METHOD FOR SUBDIVIDING DUCT INTO MEASURING AREAS OR ZONES

APPENDIX I

INSTRUMENTATION FOR DETERMINING GAS VELOCITY

A variety of instruments are available for the measurement of gas velocity in a duct or stack. The selection and use of these instruments are discussed in the Code.

On the following pages are illustrations of the most commonly used types of Pitot tubes and another instrument for this purpose, the Fecheimer probe.

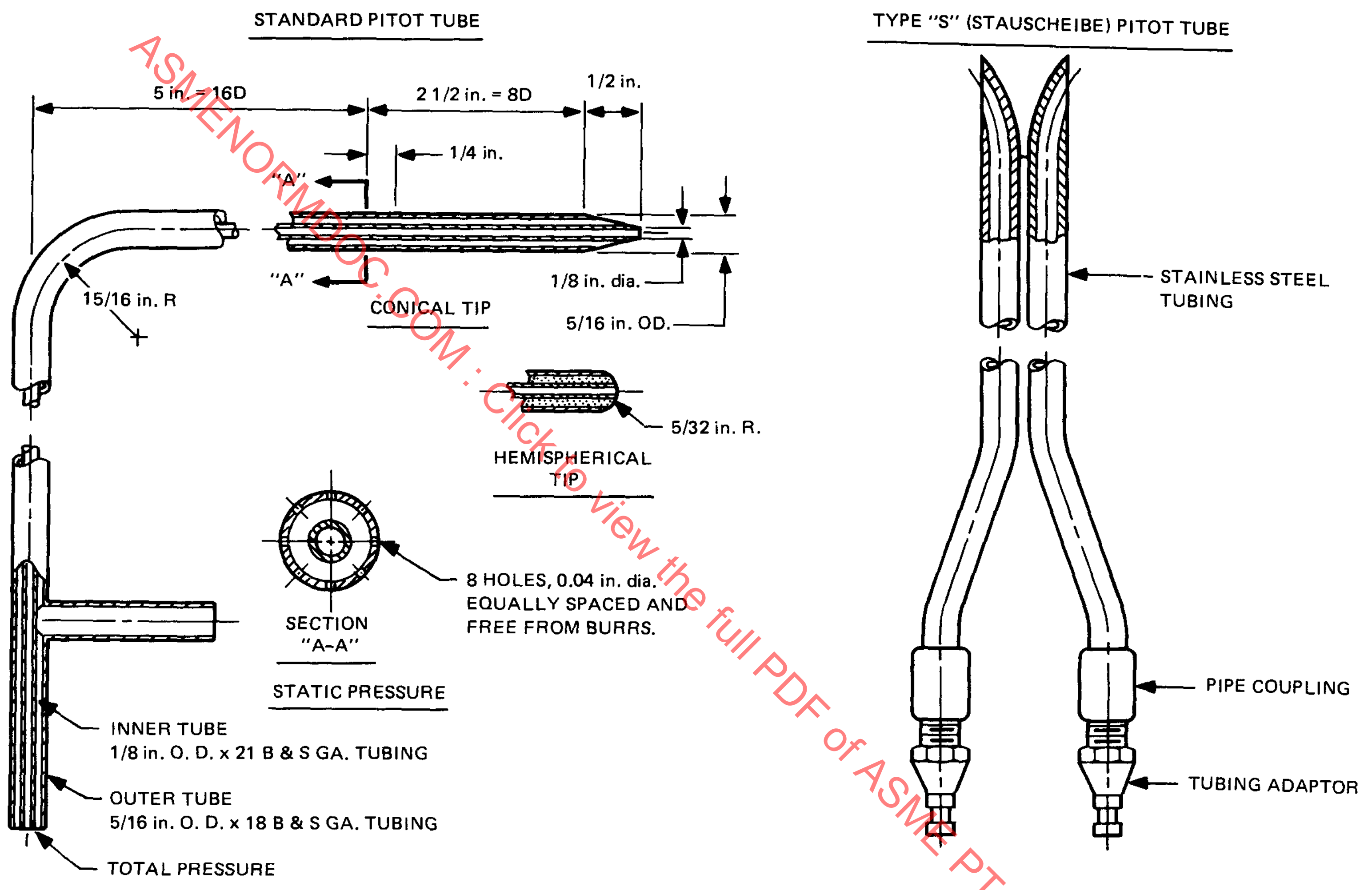


FIG. I-1 PITOT TUBES FOR DUCT GAS VELOCITY DETERMINATION

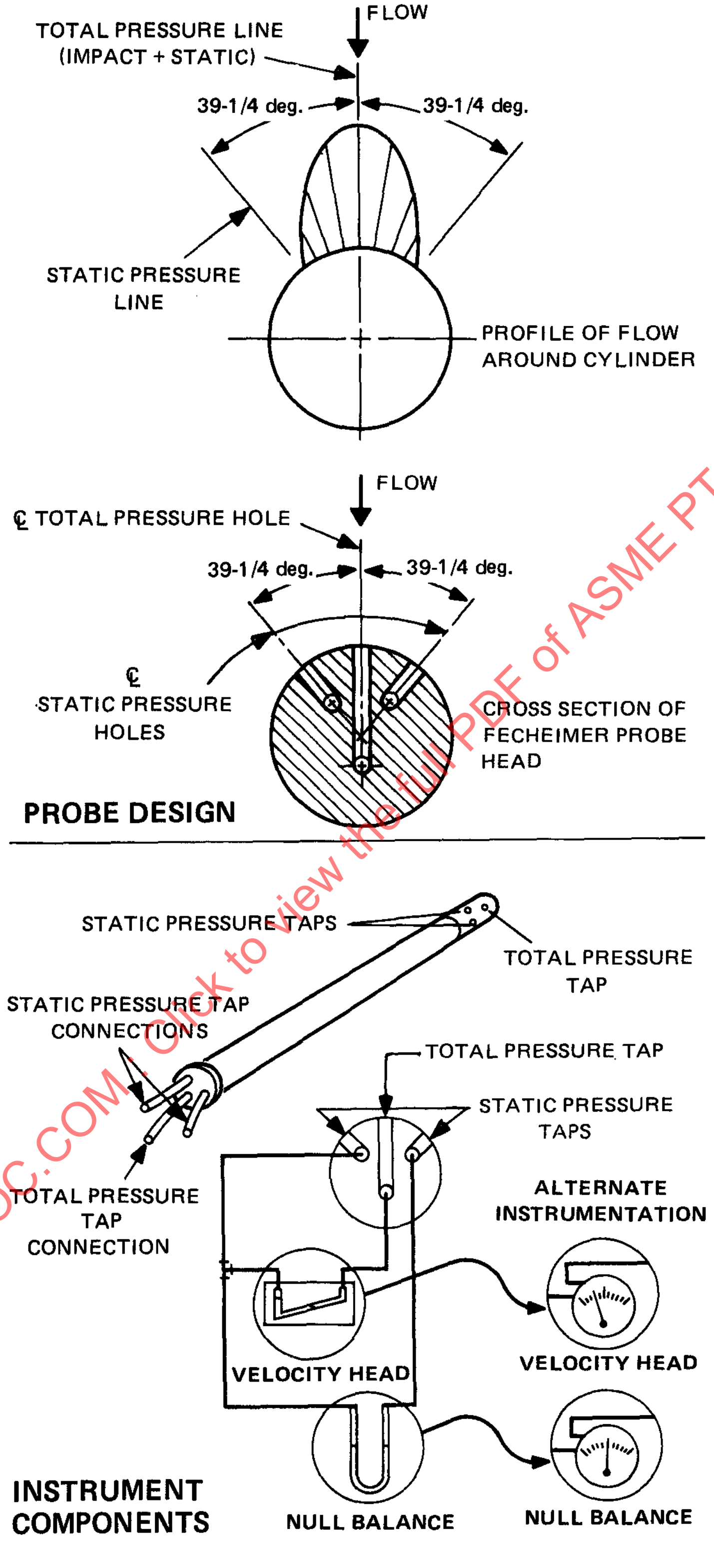


FIG. I-2 FECHEIMER PROBE – FOR AIR AND GAS FLOW MEASUREMENT
(See Reference [33], Section 7, for description of operating principles)

APPENDIX J

DESIGN AND CONSTRUCTION OF FIELD OPERATING GRAPHS

Isokinetic Sampling System

The following discussion describes a particulate sampling system, to assure isokinetic sampling, which is based on the fact that variations in gas *velocities* and gas *temperatures* are the only values that need to be monitored closely during the sampling operation. In contrast, all of the other parameters exert a relatively small influence so that their magnitude can be predicted with a high degree of precision. This provides the basis for the design of a simple "Operating Graph" which dictates flowmeter settings required during the test.

There is always some departure from isokinetic flow rates regardless of the guidance system and the procedures used—one's objective is to minimize that gap. The systems described in this Section are capable of a high degree of conformity with the isokinetic sampling rule. A departure of 2 to 3 percent is common, but it can almost always be less than 5 percent.

Construction of an Operating Graph

The procedure described below involves preparation of field operating graphs. One graph indicates required sampling rates in mass units while the other, also in mass units, indicates the flowmeter settings required to deliver the proper flow.

Construction of the first graph is based on prediction of two of the three factors which determine gas density — apparent molecular weight and pressure. It is easily possible to predict *gas densities* within 10 percent, and since flow rate through an orifice flowmeter is proportional to the square root of density, this means that the *sampling rates* indicated by the graph would, in this extreme case, be well below the allowable 10 percent departure from isokinetic flow.

The operating graph illustrated by Graph A (Figs. J-1 and J-2) expresses the gas sampling rates required, in mass units, for a ¼ in. probe (0.00034 ft^2 area) as a function of velocity pressure (h_v) and gas density (ρ_s). A measurement of the velocity pressure and gas temperature in the field indicates immediately, according to the graph, the required gas flow rate corresponding to isokinetic sampling, G_1.

The lower charts, Graphs B and C, are the operating lines for the indicating (orifice) flowmeters, the rates of which are given also in mass units. The alignment of the two graphs permits rapid selection of the flowmeter setting, (h_{fm}) required to comply with the demands indicated by Graph A.

I. Graph for Required Sampling Rate, G$_1$

The required sampling rate for isokinetic flow is expressed in mass units and transformed as indicated in the following:

$$
\begin{aligned}
\text{Required lb/min (G)} &= (\text{lb/ft}^3)\ (\text{ft}^3/\text{min}) \\
&= (\rho_s)\ (V)\ (A_0) \\
&= \rho_s\ (1096)\ (A_0)\ \sqrt{\frac{h_v}{\rho_s}} \qquad (1) \\
&= 1096\ (A_0)\sqrt{\rho_s \cdot h_v}
\end{aligned}
$$

Construction of Graph — Required Operating Rate

The value of ρ_s, density of the stack gas at temperature, T_s, is:

$$\rho_s = \frac{MW_w}{359} \times \frac{492}{460 + T_s} \times \frac{P_{sd}}{29.92} \qquad (2)$$

Example 1: Graph A, Fig. 1, is an example in which a fixed value of 30 for apparent molecular weight (MW_m) and an absolute pressure of 29.92 in. (P_{sd}) were predicted. With these values fixed, the expression for stack gas density is:

$$
\begin{aligned}
\rho_{s-1} &= \frac{30}{359} \cdot \frac{492}{460 + T_s} \\
&= \frac{41.1}{460 + T_s}
\end{aligned}
$$

When this is inserted in equation (1), we obtain the following equation for use in the construction of the graph:

$$\text{Required lb/min, } G_1 = 7030\, A_0 \sqrt{\frac{h_v}{460 + T_s}} \qquad (3)$$

Substitute the appropriate value of probe area (A_0, ft^2), then various values of temperature and plot them on log-log paper as illustrated in Graph A, Fig. J-1.

Symbols

As indicated in the list of symbols, G represents sample gas flow rate and ρ, gas density. In the development of relationships below, it is necessary to refer to these and other quantities at different places and different conditions: in the duct or stack, flowmeter gas (dry), flowmeter gas (moist), etc.; and at different times, i.e., before and after the test. A system of subscript labels is employed to aid in keeping the identity of particular quantities clear and distinct.

Subscripts -1 and -2

The label -1 attached to any quantity indicates a value that was selected for use before the test. The quantity so labeled is variously referred to as "predicted," "planned," "assumed," and the value used in a statement of "intended" sampling rate. Its *raison d'etre* is simply to distinguish these quantities which were estimated or assumed before the test, from the values available later from the test data itself, i.e., "correct" values.

The post-test "correct" values are labeled -2 and their primary application is for calculation of "departures from isokinetic sampling."

G-Values

The symbol G represents sampling rate of the raw, moist stack gas ("planned" or "correct") as represented by Graph A in Figs. J-1 and J-2.

The subscript *-fm* designates flowmeter flow rates. There are two sampling train arrangements affecting this label. One places the flowmeter at a point following a condenser and drier, which removes all moisture. In that case the flowmeter handles dry gas and this is indicated by the addition of the letter *-d* (for dry) in the subscript.

In another arrangement the flowmeter is located to measure a sample of raw, moist stack gas before any condensation can occur, and this is indicated by the additional letter *-m* (for moist) in the subscript.

The same identification symbol (*m* or *d*) is used to distinguish the molecular weight of moist stack gas (MW_m) from that of dry gas at a flowmeter (MW_d).

Gas Density – ρ

Stack gas densities are identified by the subscript *-s* and densities of gas passing through the flowmeter by *-fm*. Flowmeter gas densities which pertain to moist stack gases are further identified by the additional letter *-m* (moist); and those pertaining to flowmeter gases which follow a drying system, by the letter *-d* (dry).

II. Flowmeter Graphs

Having constructed the graph for "Required Sampling Rate," it remains to provide a graph for the indicating flowmeter which measures sample flow, one of whose coordinates is also lb/min, the other h_{fm}, i.e., the meter reading.

The use of an orifice flowmeter which *indicates* flow is necessary to implement these sampling procedures. This flowmeter provides instantaneous indication of flow rate and if one plots its calibration curve in weight units, provides graphical means whereby the sampling flow requirements can be read from the graph; and a basis also for adjusting the flow rate while referring to the flowmeter indicator.

The two common positions of the flowmeter are (A) downstream from a condenser-dessicant system, and (B) preceding all elements of the train except the sample filter, and maintained at elevated temperatures to avoid condensation. Each requires a different type of graph.

(A) Flowmeter Following a Condenser – Graph B, Fig. J-1

Where the train has a condenser preceding the flowmeter, only the *dry gas* portion of the flow (G_{fm-1d}) will be indicated by the flowmeter. The remainder (G_{cond-1}) is removed by the condenser and the following relationships apply:

$$\begin{array}{ccccc} \text{Required sample flow rate} & = & \text{Metered dry gas flow rate} & + & \text{H}_2\text{O condensation rate} \\ G_1 & \Leftrightarrow & G_{fm-1d} & + & G_{cond-1} \end{array} \tag{4}$$

$$\text{Note that:} \quad G_{cond-1} = \frac{\text{lb H}_2\text{O}}{\text{lb dry gas}} \cdot \frac{\text{lb dry gas}}{\text{min}} = M_1 \cdot G_{fm-1d}$$

$$\text{from which} \quad G_{fm-1d} = \frac{G_1}{1 + M_1} \tag{5}$$

These equations imply the practical fact that the condenser desiccant system is intended to remove all of the moisture represented by H_1.

The resulting flowmeter graph for numerous values of M_1 is shown as Graph B, Fig. J-1.

Where humidity is zero the values of G_{fm-1d} are the same as G_1 (Graph A). For positive values of water content, M_1, the correct flowmeter setting, G_{fm-1d}, is a value displaced from G_1 by the fraction $\frac{1}{1+M_1}$.

(B) Flowmeter at Elevated Temperature (Omitting Condenser) – Graph C, Fig. J-2

It may be convenient in some cases to employ a sampling train which maintains the temperature of the flowmeter above the dewpoint, and which dispenses with a condenser altogether.

In such an arrangement a different type of operating graph illustrated by Graph C, Fig. J-2, is employed.

It can be used wherever the flowmeter temperature is maintained above the dewpoint, including those arrangements which dispose the flowmeter within the stack and thus maintain it at stack temperature. It is also applicable to *high volume sampling trains* where there is minimal cooling of gases before the flowmeter.

The principles and procedures for construction of such a graph are illustrated in the following description, and Graph C.

Construction of Graph C

First, derive an equation relating flowmeter delivery, G_{fm}, to flowmeter setting, h_{fm}, based on the flowmeter calibration line, which will be used to draw several temperature lines as illustrated in Graph C, Fig. J-2. To accomplish this, derive the value of K in the following equation for weight flow rate through the orifice meter.

$$G_{fm-1w} = K\sqrt{h_{fm}\cdot\rho_{fm-1w}} \qquad (6)$$

Example 2: The value of K is found by using data given by the calibration line.

Let the flowmeter of Graph B, Fig. J-1, serve in the present application. Select any point for values of G_{fm-1w} and h_{fm}, e.g., 0.073 and 2.0, respectively, from the 100°F line (ρ_{fm-1w} = .071 is density at 100°F). Then –

$$K = \frac{0.073}{\sqrt{2.0\,(.071)}} = 0.20$$

From which –

$$h_{fm} = \left(\frac{G_{fm-1w}}{0.20}\right)^2\cdot\left(\frac{1}{\rho_{fm-1w}}\right) \qquad (7)$$

The basic value of ρ_{fm-1w} is the density of the stack gas, ρ_{s-1}, adjusted for any difference in temperature T_{fm}, and also any significant pressure difference between stack and flowmeter (P_{sd} vs P_{fm}) that may occur due to pressure drop across the sample filter. P_{fm} is the average predicted flowmeter pressure during the run.

Suppose the flowing gas in the stack is predicted to have an average molecular weight of 30, and to be at an absolute pressure of 29.92 in. Hg, average pressure drop across the filter during the run is predicted to be 1 in. Hg. Flowmeter gas density, ρ_{fm-1w}, is then

$$\rho_{fm-1w} = \frac{30}{359}\times\frac{492}{460+T_{fm}}\times\frac{28.92}{29.92}$$

$$= \frac{39.7}{460+T_{fm}}$$

Substituting this value of flowmeter gas density in equation (7) gives:

$$h_{fm} = \left(\frac{G_{fm-1w}}{0.20}\right)^2\cdot\left(\frac{460+T_{fm}}{39.7}\right) \qquad (8)$$

Each value of flowmeter temperature, t_{fm}, which is to be represented in the finished graph, is inserted in equation (8), followed by plotting values of G_{fm-1w} and h_{fm}.

The flowmeter graph resulting from these operations appears in Fig J-2 as Graph C in the assembly with Graph A previously described.

Alternate Graph

When the sample train flowmeter is at elevated temperatures, it may be desirable to use an alternate operating graph. The construction and use of such a graph is described below. It can be used where the stack temperature and pressure are known and remain reasonably constant.

The use of the graph is illustrated by Fig. J-3 where an example of an application is shown for an assumed stack gas temperature and pressure. The design of the graph is based upon the following relationships:

Pitot tube; $V = 1096\sqrt{\frac{h_v}{\rho_s}}$

Let Q_s = volume rate of gas sampled at stack conditions and Q_{fm} = volume rate of gas sampled at orifice conditions.

Then $Q_s = A_0\,V = 1096A_0\sqrt{\frac{h_v}{\rho_s}}$

and $Q_{fm} = K\sqrt{\frac{h_{fm}}{\rho_{fm}}}$

but $Q_{fm} = Q_s \times \frac{\rho_s}{\rho_{fm}}$

thus $$K\sqrt{\frac{h_{fm}}{\rho_{fm}}} = 1096\,A_0 \cdot \frac{\rho_s}{\rho_{fm}} \cdot \sqrt{\frac{h_v}{\rho_s}}$$

$$K^2\,\frac{h_{fm}}{\rho_{fm}} = \left(1096\,A_0 \times \frac{\rho_s}{\rho_{fm}}\right)^2 \times \frac{h_v}{\rho_s}$$

$$h_{fm} = \frac{\rho_{fm}}{K^2}\left(1096\,A_0 \times \frac{\rho_s}{\rho_{fm}}\right)^2 \times \frac{h_v}{\rho_s}$$

$$h_{fm} = \left(\frac{1096\,A_0}{K}\right)^2 \times \frac{\rho_s}{\rho_{fm}} \times h_v$$

but $$\frac{\rho_s}{\rho_{fm}} = \frac{T_{fm}}{T_s} \times \frac{P_{sd}}{P_{fm}}$$

thus $$h_{fm} = \left(\frac{1096\,A_0}{K}\right)^2 \times \frac{T_{fm}}{T_s} \times \frac{P_{sd}}{P_{fm}} \times h_v$$

For any given sampler configuration, A_0 and K are constant, so that it is only necessary to consider the variables $\frac{T_{fm}}{T_s}$ and $\frac{P_{sd}}{P_{fm}}$.

When constructing the graphs for a given test, the stack temperature, T_s, and pressure, P_{sd}, may be measured prior to the start of the test, and the planned flowmeter differential h_{fm}, will then only depend upon T_{fm}, P_{fm}, and h_v, which can be read from instruments while sampling, and corrections to the sampling rate graphically calculated, so as to continuously maintain isokinetic conditions. Deviations from isokinetic will be quite small, as they will be caused only by unexpected variations in the duct temperature and pressure.

The attached example is based upon the following assumed values:

A_0 = 0.001 sq ft
K = 0.95
T_s = 800°R (340°F)
P_{sd} = 30 in. Hg

Note that for added convenience, the correction lines for P_{fm}, the absolute pressure at the orifice meter, could have been labeled with the static pressure (negative) actually measured at the orifice meter, as the barometric pressure must be known in any case.

III. Calculating Departures from Isokinetic Sampling

The results of particulate concentration derived from runs where sampling was performed within 10 percent of isokinetic rates are valid results, and no adjustment is required.

It is, however, appropriate to calculate and report the magnitude of the departure from isokinetic rates for each run, indicated by the ratio:

$$\frac{\text{Actual moist gas sampling rate}}{\text{Correct moist gas sampling rate}}$$

Methods of calculation are given in the following for the two types of sampling trains.

(A) Flowmeter Following a Condenser-Desiccant Unit

The sampling rates are given by the sum of two streams: that represented by the condensation rate, G_{cond}, plus the dry gas rate measured by the flowmeter, G_{fm}.

Actual Sampling Rate

$$\text{Planned moist gas sampling rate} = G_{fm-1d} + G_{\text{cond}-1} \qquad (9)$$

The planned dry gas sampling rate, W_{fm-1d}, was based on pre-test estimates of dry gas density at the flowmeter, ρ_{fm-1d}. The following equation uses the known gas density, ρ_{fm-2d} to derive *actual* dry gas flow.

$$\begin{aligned}\text{Actual moist gas sampling rate} &= G_{fm-2d} + G_{\text{cond}-2} \\ &= G_{fm-1d}\sqrt{\frac{\rho_{fm-2d}}{\rho_{fm-1d}}} + G_{\text{cond}-2}\end{aligned} \qquad (10)$$

The average value of planned sampling rates, G_{fm-1d} and the values making up density of dry gas at the flowmeter, ρ_{fm-1} and ρ_{fm-2}, are obtained directly from the test log sheets. The quantity of collected water, $G_{\text{cond}-2}$, is the measured quantity for condenser and desiccant.

Correct Sampling Rate

The correct sampling rate, W_2, is represented by equations (1) and (2) using the correct values of moist stack gas molecular weight, MW_w, and absolute pressure in the stack, P_{sd-2}, which together with temperature, determine the density ρ_s.

$$\text{Correct moist gas sampling rate} = G_2 = G_1\sqrt{\frac{\rho_{s-2}}{\rho_{s-1}}} \qquad (11)$$

Individual values of required sampling rates will have been recorded on the log sheets from which the average value, W_1, will be calculated for present purposes.

The density corrections indicated in equation (11) are as follows:

$$G_2 = G_1\sqrt{\frac{MW_{m-2}}{MW_{m-1}} \times \frac{P_{sd-2}}{P_{sd-1}}} \qquad (12)$$

The departure from isokinetic rates is now given by the ratio –

$$\frac{\text{Actual sampling rate}}{\text{Correct sampling rate}} = \frac{\text{Equation (10)}}{\text{Equation (12)}}$$

(B) Flowmeter at Elevated Temperatures

During the sampling which employs the type of operating graph illustrated by Graph C, the flowmeter temperature is intended to be constant. If there be any fluctuation, the flow would be immediately regulated, changing the flowmeter indicator setting h_{fm} (ordinate in Graph C) by an appropriate amount.

In either case the "actual" sampling rate would be no different from the "planned" rate. Therefore as indicated on the Graph C abcissa scale, the metered gas flow rate W_{fm-1w} is the same as W_1, i.e.:

$$\begin{array}{ccccc} \text{Planned} & & \text{Actual} & & \text{Required} \\ \text{Sampling} & = & \text{Sampling} & = & \text{Sampling} \\ \text{Rate} & & \text{Rate} & & \text{Rate} \end{array}$$

$$G_{fm-1w} = G_{fm-2w} = G_1$$

The correct sampling rate previously described, equations (11) and (12) above, applies equally in this system:

$$\text{Correct sampling rate} = G_2 = G_1 \sqrt{\frac{\rho_{d-2}}{\rho_{d-1}}} \qquad (13)$$

From which the departure from isokinetic sampling is given by the ratio:

$$= \frac{\text{Actual sampling rate}}{\text{Correct sampling rate}}$$

$$= \frac{G_1}{G_2} = \frac{\text{Equation (13)}}{\text{Equation (12)}}$$

The equation forms below illustrate the use of test data in the calculation of departure from isokinetic sampling:

(1) Correct (isokinetic) sampling rate $= G_2$

$$G_2 = G_1 \sqrt{\frac{MW_{m-2}}{MW_{m-1}} \times \frac{P_{sd-2}}{P_{sd-1}}}$$

$$= G_1 \sqrt{\frac{\rule{2cm}{0.4pt}}{30} \times \frac{\rule{2cm}{0.4pt}}{29.92}}$$

(2) Actual (moist gas) sampling rate

$$= \begin{array}{c}\text{Measured} \\ \text{dry gas rate}\end{array} + \begin{array}{c}\text{Measured} \\ \text{cond. } H_2O\end{array}$$

$$= G_{fm-2d} + G_{cond-2}$$

$$= G_{fm-1d} \sqrt{\frac{P_{fm-2}}{29.92} \times \frac{460 + 70}{T_{fm}} \times \frac{MW_{d-2}}{29}}$$

$$= \rule{1cm}{0.4pt} \sqrt{\frac{\rule{1cm}{0.4pt}}{29.92} \times \frac{530}{\rule{1cm}{0.4pt}} \times \frac{\rule{1cm}{0.4pt}}{29}}$$

(3) $\% \text{ Isokinetic} = \frac{[\#2]}{[\#1]} \rule{1cm}{0.4pt} \times 100 = \rule{1cm}{0.4pt} \%$

LOG SHEET DESIGN

Implementation of this system requires systematic recording of test data. Following is a list of data required to be recorded in the field log sheet.

Data	Symbols
Data or samples for subsequent determination molecular weight	
Dry gas composition: CO_2, O_2, N_2, etc.	MW_d
Moisture content: H_2O	MW_m
Spot measurements, stack	
Gas velocity pressures	h_v
Gas temperatures	T_s
Barometric pressure and stack static pressure	P_{sd-2}
Operating data from graph, etc.	
Sampling times	
Planned moist gas sampling rate, Graph A	G_1
Planned dry gas sampling rate, Graph B	G_{fm-1d}
Flowmeter static pressure	P_{fm-2}
Flowmeter temperature	T_{fm-2}

Graph A

Required gas flow rate for ¼ in. probe:

$$A_0 = 0.00034 \text{ ft}^2$$

$$G_1 = 1096\, A_0 \sqrt{\rho_{d-1}\, h_v}$$

Graph B

Dry gas flow requirements and settings of orifice flowmeter for compliance with G_1 and M; based on gas density at flowmeter,

$$\rho_{fm-1d} = 0.075 \text{ lb/ft}^3$$

This graph is based on a predicted gas density of 0.075 lb/ft³. This prediction is not always applicable in cases when the negative pressure is large and variable.

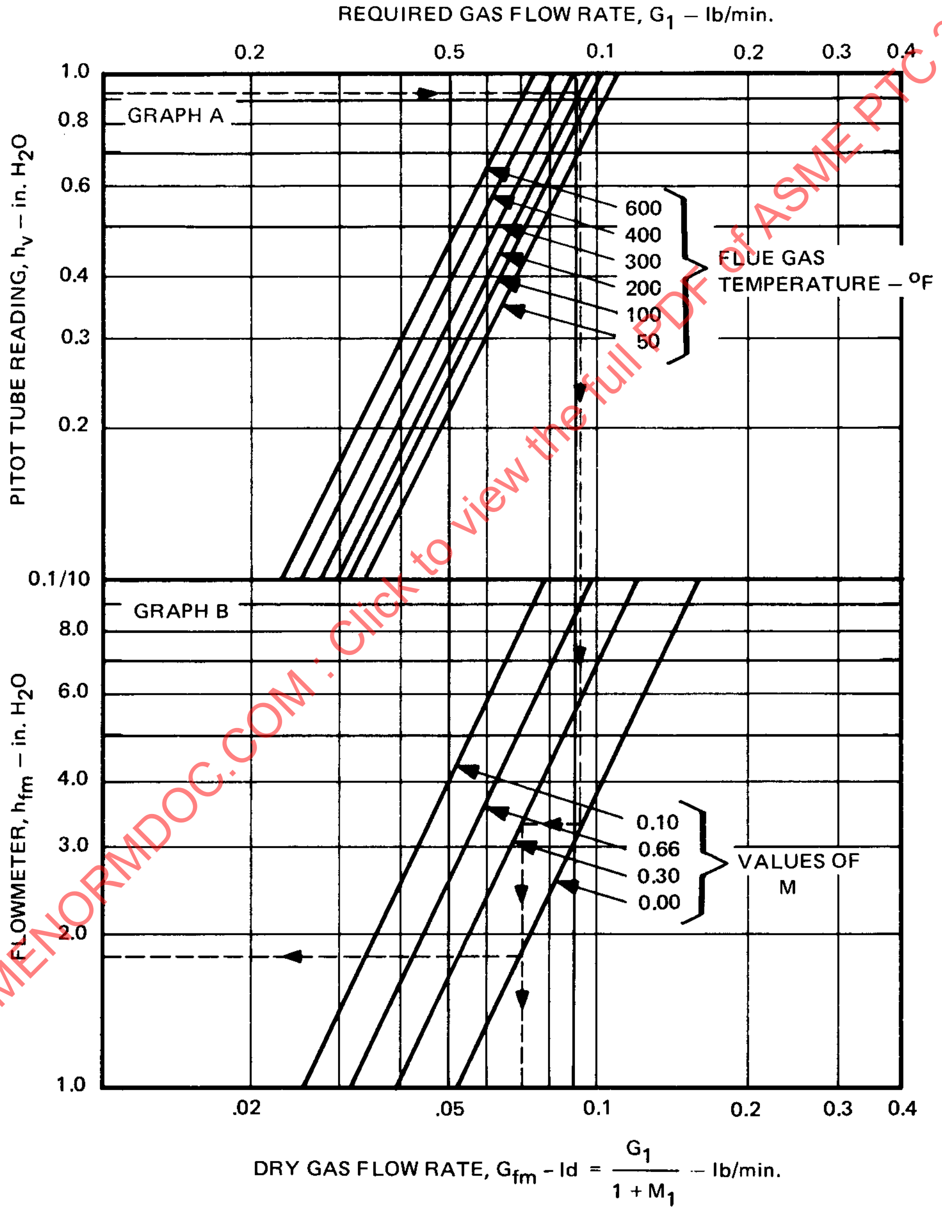


FIG. J-1 OPERATING GRAPHS

Graph A

Required gas flow rate for ¼ in. probe.

$$A_0 = 0.00034\ \text{ft}^2$$

$$G_1 = 1096\, A_0 \sqrt{\rho_{d-1}\, h_v}$$

Graph C

Orifice flowmeter for operation at elevated temperatures (above dewpoint).

$$\text{Predicted}\quad \rho_{fm-1m} = \frac{39.7}{460 + T_s}$$

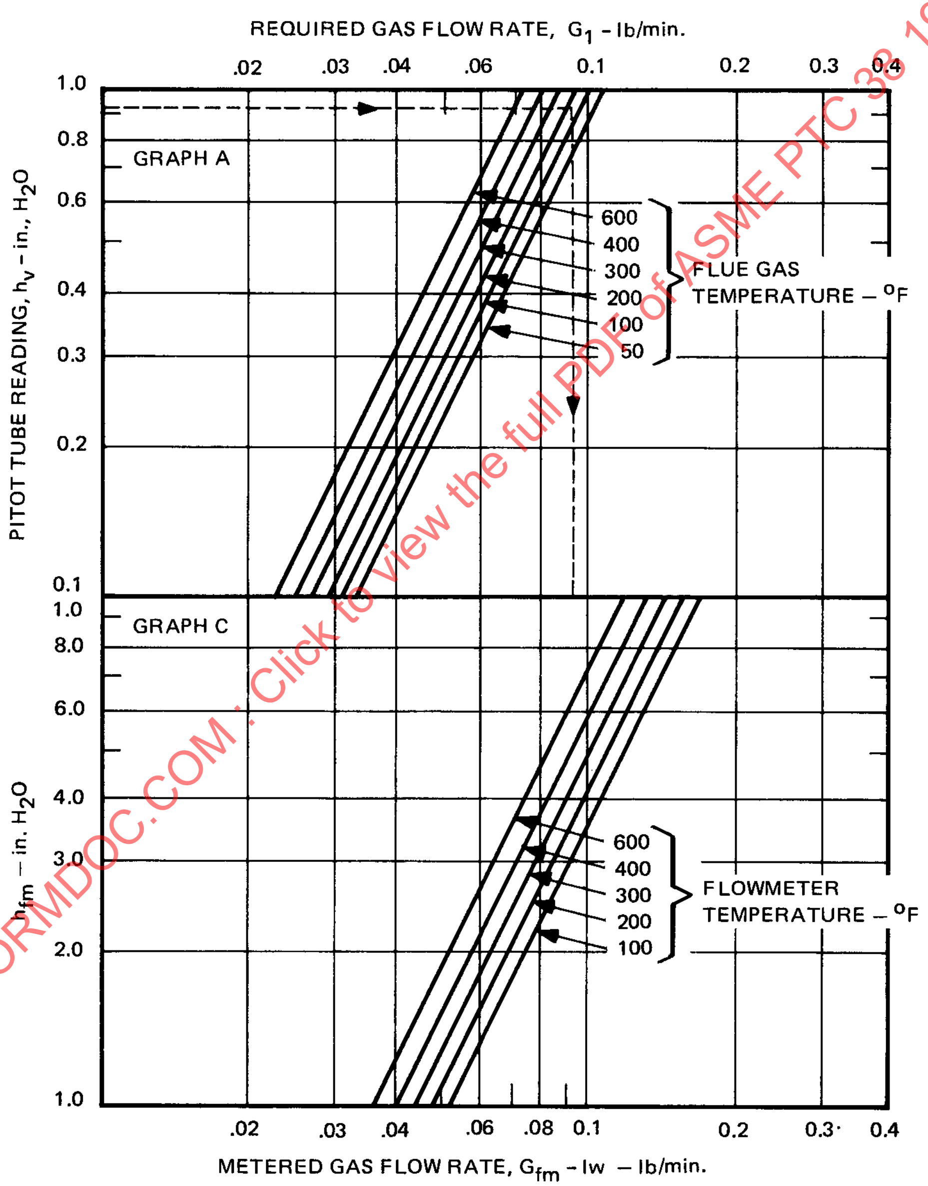


FIG. J-2 OPERATING GRAPHS

Test Constants

A_0 = 0.001 ft²
K = 0.95
T_s = 800° R (340° F)
$P_{sd'}$ = 30 in. Hg

Example

h_v = 0.95 in. H_2O
T_{fm} = 240° F
P_{fm} = 25 in. Hg
Read h_{fm} = 1.30 in. H_2O

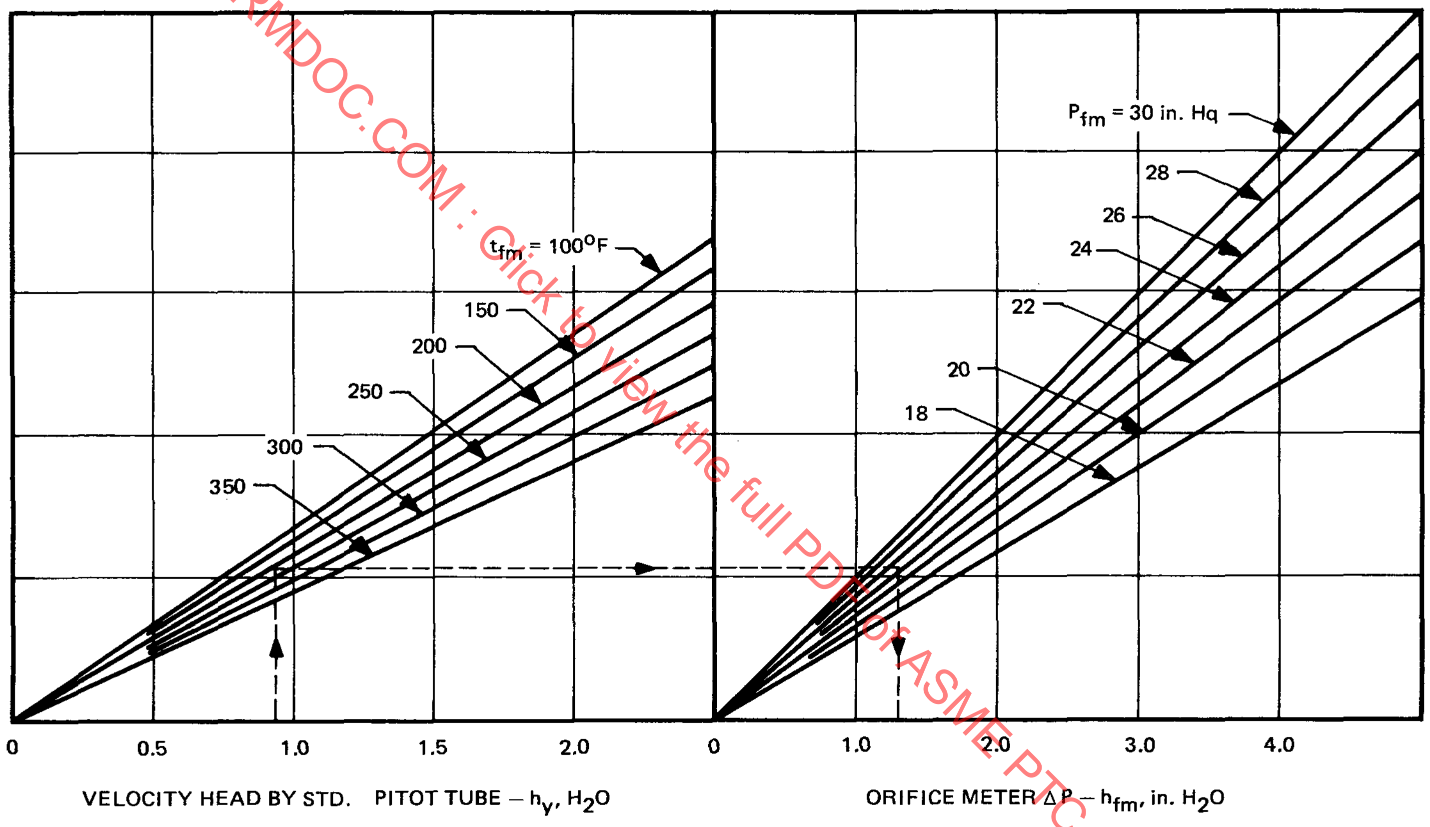


FIG. J-3 ALTERNATE OPERATING GRAPH

Symbols

V = flue gas velocity, ft/min

ρ_s = stack gas density, lb/ft^3

ρ_{s-1} = predicted gas density at stack conditions, lb/ft^3

ρ_{s-2} = actual gas density at stack conditions, lb/ft^3

ρ_{fm-1d} and ρ_{fm-1m} = dry gas and moist gas predicted gas densities, respectively, at flowmeter conditions, used in planning the Operating Graph

ρ_{fm-2d} and ρ_{fm-2m} = dry gas the moist gas densities, respectively, at flowmeter conditions that actually prevailed during the test

G_1 = planned sampling rate (moist stack gas), lb/min, based on predicted values $\rho_f\ \rho_{s-1}$ and indicated by the Operating Graph A

G_2 = correct sampling rate (moist stack gas), lb/min, based on measured value of stack gas density, ρ_{s-2}

MW_m = molecular weight, moist stack gas

MW_d = molecular weight, dry gas

G_{fm-1d} and G_{fm-1m} = flowmeter sampling rates, dry and moist gas, respectively, as planned, based on predicted flowmeter gas density, ρ_{fm-1}

G_{fm-2d} and G_{fm-2m} = flowmeter sampling rates, dry and moist gas, respectively, that actually prevailed during sampling, using flowmeter gas density ρ_{fm-2m} or ρ_{fm-2d}

G_{cond-1} = partial sampling rate due to condensation of water in condenser preceding flowmeter (predicted)

G_{cond-2} = partial sampling rate due to condensation of water in condenser preceding flowmeter (measured)

h_{fm} = flowmeter pressure differential, in. H_2O

h_v = velocity pressure, stack gas, in. H_2O

A_0 = sampling nozzle opening area, ft^2

M = stack gas humidity, lb H_2O/lb dry gas

T_s = stack gas temperature, °F

T_{fm} = flowmeter gas temperature, °F

P_{sd} = absolute pressure in stack, in. Hg (barometric pressure plus induced pressure)

P_{fm} = absolute pressure at flowmeter, in. Hg

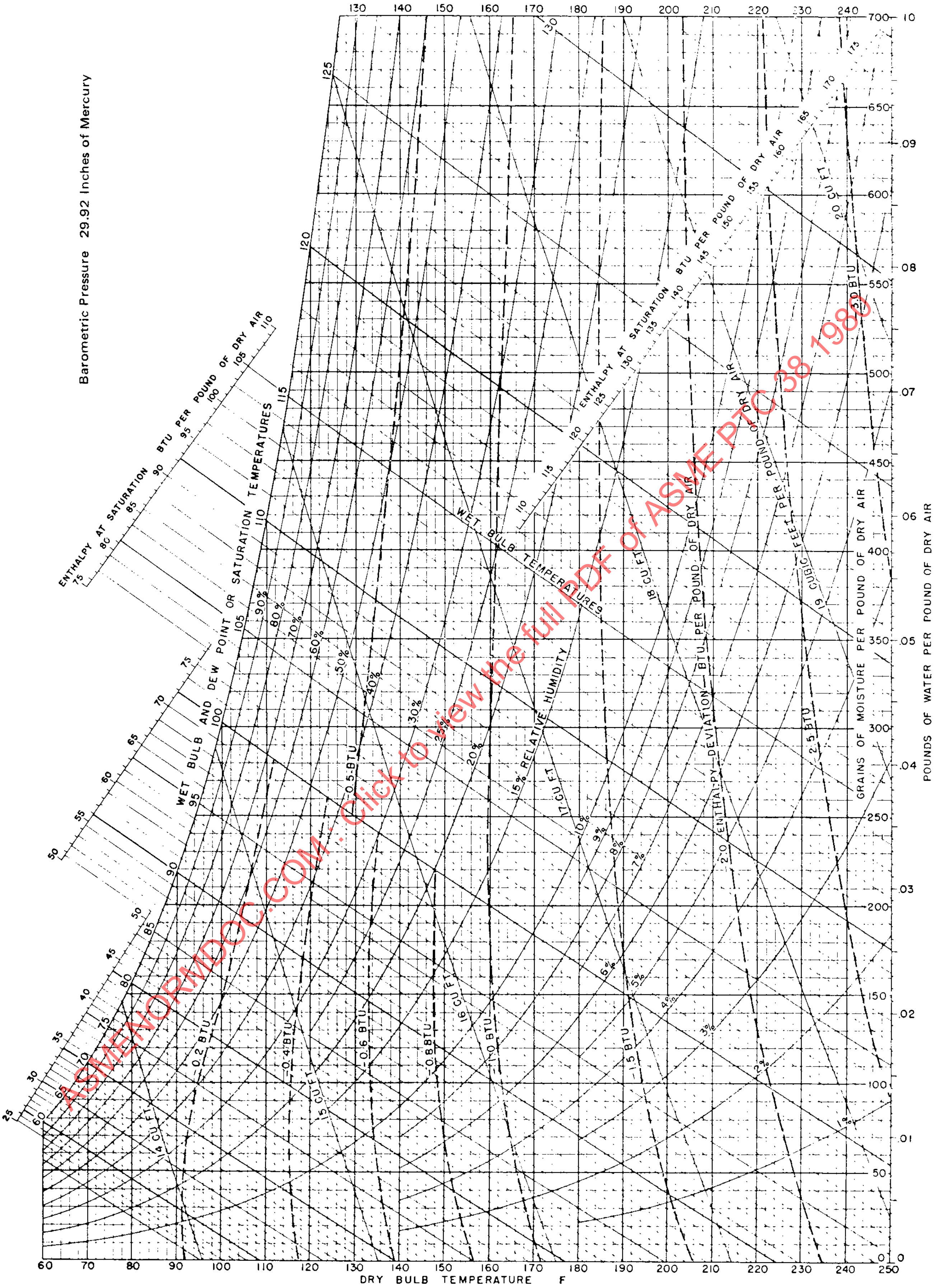
p_{fm} = static pressure at flowmeter, in. Hg

APPENDIX K

GRAPHS AND TABLES OF USEFUL DATA

Contained herein are various graphs and tables of useful data frequently used during the planning and execution of field tests and in the calculation of test results. Included are the following:

Fig. K-1	Psychrometric Chart – Low Temperatures
Fig. K-2	Psychrometric Chart – Medium Temperatures
Fig. K-3	Psychrometric Chart – High Temperatures
Fig. K-4	Table of Conversion Factors
Fig. K-5	International Atomic Weights
Fig. K-6	Combustion Constants
Fig. K-7	Temperature Conversion Table
Fig. K-8	Conversion Factors – Gas Flow Rates
Fig. K-9	Relationship Between Velocity Head and Velocity
Fig. K-10	Relationship Between Nozzle Size and Flow Rate



Barometric Pressure 29.92 Inches of Mercury

FIG. K-1 PSYCHROMETRIC CHART – LOW TEMPERATURES

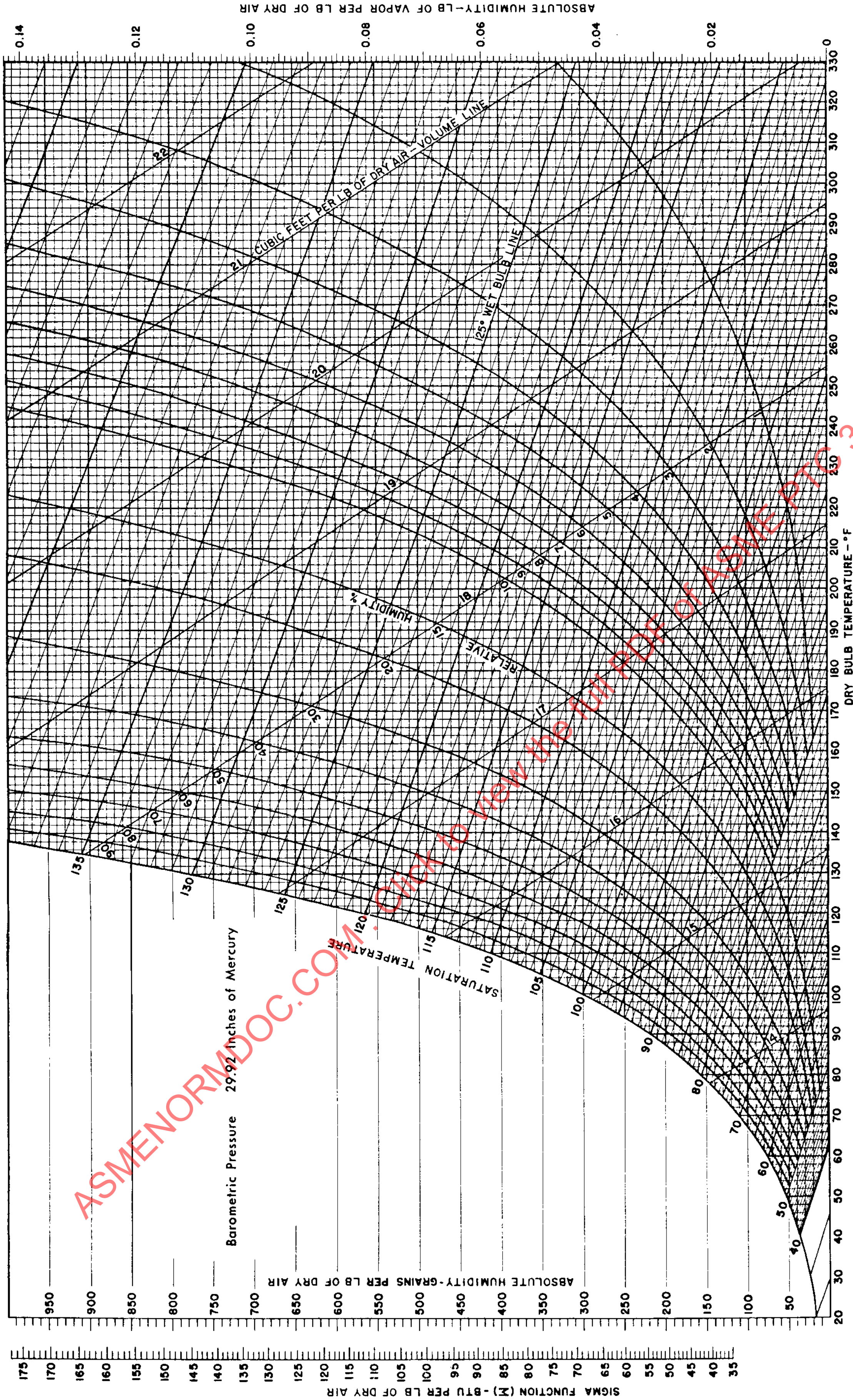


FIG. K-2 PSYCHROMETRIC CHART — MEDIUM TEMPERATURES

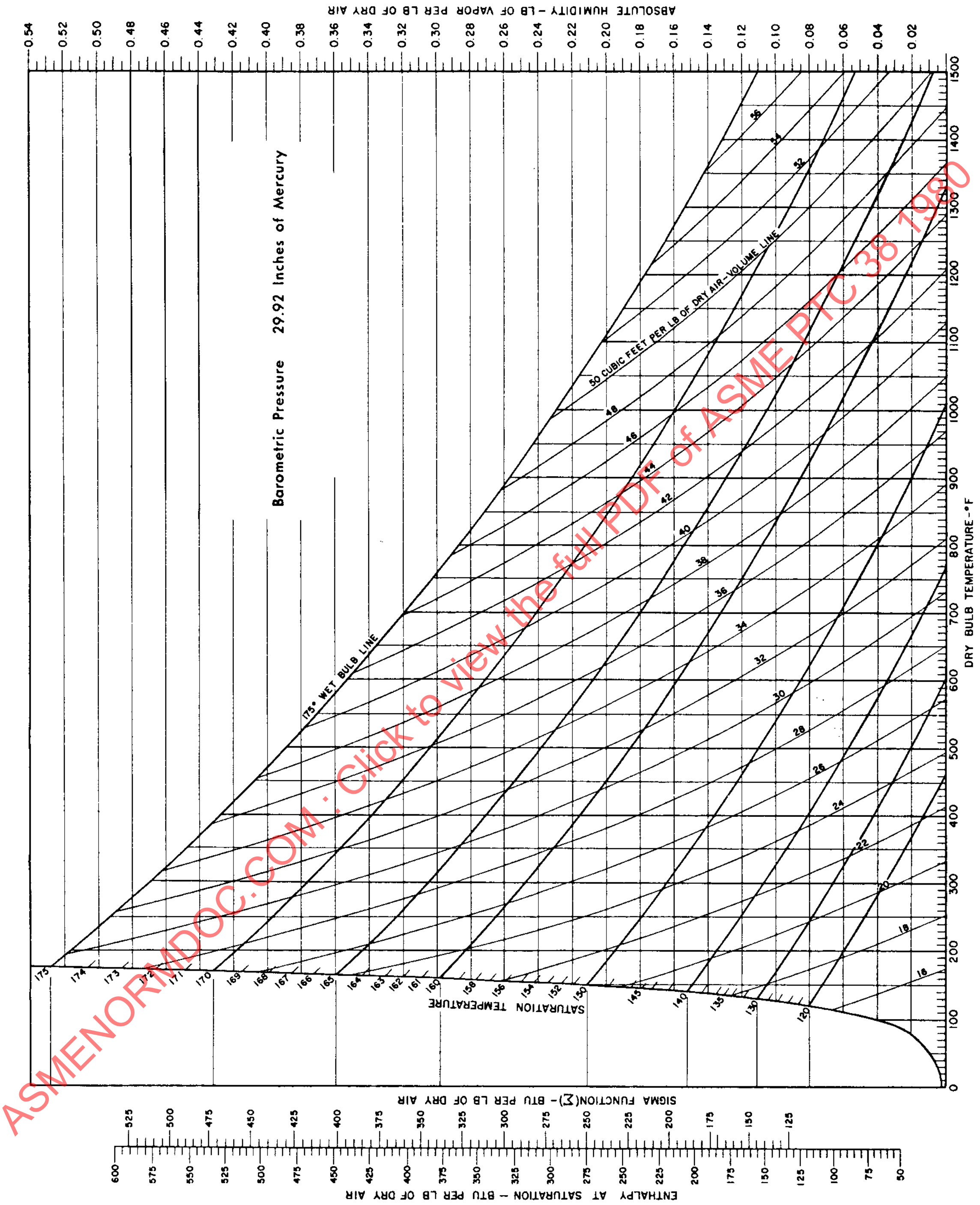


FIG. K-3 PSYCHROMETRIC CHART — HIGH TEMPERATURES