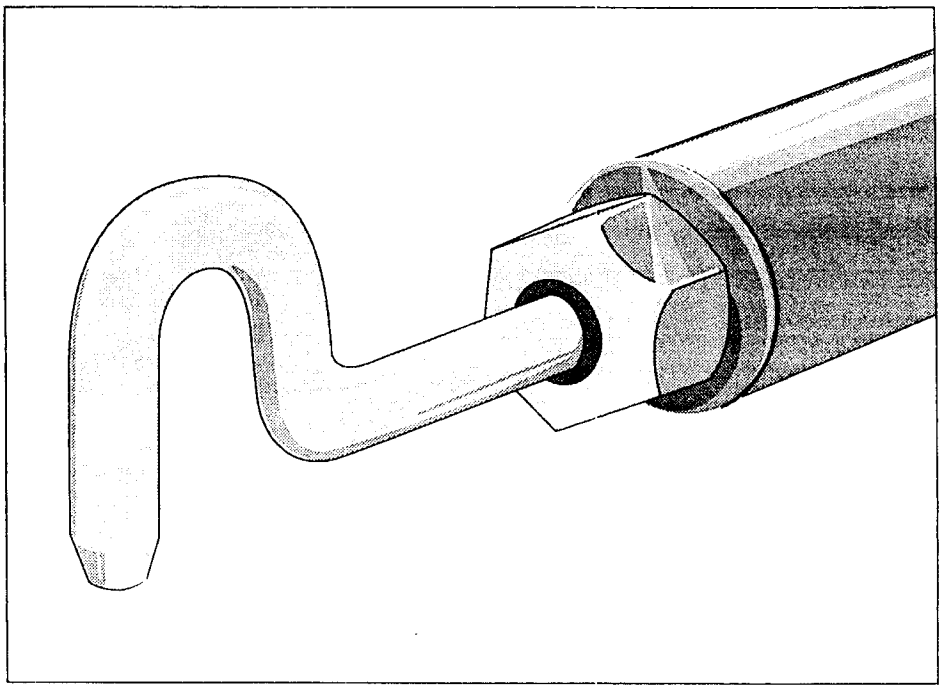
Environmental
Programs

Source Sampling for Particulate Pollutants

Student Manual

APTI Course 450

Edition 3.0



Industrial Extension Service College of Engineering North Carolina State University

Environmental
Programs

Source Sampling for Particulate Pollutants

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APTI Course 450

Edition 3.0

Revised and edited by J.A. Jahnke, Ph.D.
Source Technology Associates

Developed by North Carolina State University
EPA Cooperative Assistance Agreement CT-901889

This project has been funded wholly or in part by the United States Environmental Protection Agency under Cooperative Assistance Agreement CT-901889 to North Carolina State University. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Printed on recycled paper in the United States of America

ISBN 1-56049-021-7

3.0-05-95

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Symbols

A_n - sampling nozzle cross-sectional area

A_s - stack cross-sectional area

a - mean particle projected area

B_{wm} - percent moisture present in gas at meter

B_{ws} - percent moisture present in stack gas

C_p - pitot tube calibration coefficient

$C_{p(std)}$ - standard pitot-static tube calibration coefficient

c_s - particulate concentration in stack gas mass/volume

c_{ws} - particulate concentration on a wet basis mass/wet volume

c_{s12} - particulate concentration corrected at 12% CO_2

c_{s50} - particulate concentration corrected to 50% excess air

D_E - equivalent diameter

D_H - hydraulic diameter

D_n - source sampling nozzle diameter

E - emission rate - mass/heat Btu input

ε - electric field strength

μ_ε - electric mobility

e - base of natural logarithms (ln10 = 2.302585)

%EA - percent excess air

F_c - F sub c factor using c_s and CO_2 on a wet or dry basis

F_d - F sub d factor using c_s and O_2 on a dry basis

F_w - F sub w factor using c_{ws} and O_2 on a wet basis

F_o - F sub o factor used for checking Orsat data

$\Delta H_@$ - Pressure drop across orifice meter for 0.75 cfm flow rate at standard conditions

ΔH - pressure drop across orifice meter

j - the j^{th} traverse point

K - factor used in the isokinetic rate equation (a function of many variables)

K_p - pitot tube equation dimensional constant metric units

$$34.97 \frac{m}{sec} \left(\frac{(g/g-mole)\ (mmHg)}{(°K)\ (mm\ H_2O)} \right)^{1/2}$$

English units

$$85.49 \frac{ft}{sec} \left(\frac{(lb/lb-mole)\ (in.\ Hg)}{(°R)\ (in.H_2O)} \right)^{1/2}$$

m - mass

M_d - dry gas molecular weight

M_s - wet stack gas molecular weight

n - number of moles

P_{atm} - atmospheric pressure

P_b - barometric pressure ($P_b = P_{atm}$)

P_m - absolute pressure at the meter

pmr - pollutant mass rate

p_s - stack static pressure (gauge pressure)

P_s - absolute pressure in the stack

P_{std} - standard absolute pressure

metric units = 760 mm Hg
English units = 29.92 in. Hg

Δp - gas velocity pressure

Δp_{std} - standard velocity pressure read by the standard pitot tube

Δp_{test} - gas velocity pressure read by the Type S pitot tube

ρ - gas density

Q_s - stack gas volumetric flow rate corrected to standard conditions

R - gas law constant

t - temperature (degrees Fahrenheit or degrees Celsius)

T_m - absolute temperature at the meter

metric units = °C + 273 = °K
English units = °F + 460 = °R

T_s - absolute temperature of stack gas

T_{std} - standard absolute temperature

metric units = 20°C + 273 = 293°K

English units = 69°F + 460 = 528°R

V_m - volume metered at actual conditions

$V_{m(std)}$ - volume metered corrected to standard conditions

v.p. - water vapor pressure

v_d - drift velocity

v_n - nozzle velocity

v_s - stack gas velocity

W - width of the duct cross-section at the sampling site

Q - time in minutes

Subscripts

atm - atmospheric

avg - average

b - barometric

corr - corrected

d - dry gas basis

f - final

g - gauge

i - initial

m - at meter

n - at nozzle

p - of pitot tube

s - at stack

scf - standard cubic feet

spir - spirometer

std - standard conditions

T - total

th - theoretical

w - wet basis

Preface

This manual is an update of the Course 450 Student Manual EPA 450/2-79-006 written and edited by G.J. Aldina and J.A. Jahnke. This document was an outgrowth of earlier student manuals developed by W. Smith, R. Shigehara, W. DeWees and many others. The basic Method 5 isokinetic source testing procedures have not changed appreciably since their inception in the 1970s. However, there have been changes in focus: more emphasis on PM_{10} sampling, newer methods for determining isokinetic sampling rates, and greater attention to quality assurance procedures. This revised manual attempts to update the old, while retaining the detailed technical information and equation derivations that were found convenient in the past.

The scope of this manual is limited to the basic isokinetic particulate sampling method and does not address the advanced source sampling methods developed during the 1980s. These advanced techniques are specialized in nature and should be studied after the concepts of isokinetic sampling and source sampling are understood and have been practiced. Detailed information on advanced topics may be found through the US EPA Emission Monitoring Technology Information Center (EMTIC) and workshops presented by EMTIC.

Chapter 1

Introduction to Source Testing for Particulate Matter

Particles are emitted into the atmosphere by both natural processes and human activities. Although we can do little about natural phenomena, the release of particles into the atmosphere from human activities can be minimized by adding controls to emission sources, such as incinerators and power plants, or by changing the way we do things. But why should we minimize such emissions? Basically, because they affect our health and welfare. High concentrations of particles in the atmosphere can cause respiratory illness, obscure visibility, cause material and agricultural damage, and affect our psychological well-being.

If we attempt to reduce particulate emissions by controlling or changing our emission sources, we should have some way of determining whether we have been successful. This is where source testing comes in. Source testing methods are used to tell us how we are doing in controlling emissions.

Particulate Matter

Particulate matter is the finely divided solid or liquid material found in a flue gas (not including uncombined water). This material is, of course, composed of particles. The terminology associated with particles in air is often confusing, primarily because the problems of "smokes," "mists," and "vapors" have been of concern over the long period of man's development, especially during the more recent industrial ages. Typical terms are, for example, **dust**, **fume**, **smoke**, **mist**, and **spray**. The terms **dispersion aerosol** and **condensation aerosol** are also used, primarily in discussions relating to particles entrained in ambient air.

Particles can be described by three basic features:

1. How they are formed
2. What they are made of
3. Their size

Particle Formation and Composition

Particles can be formed by mechanical action, chemical reaction, condensation, or atomization. Solid particles can be entrained by process gases when they are handled or transported, or they can be generated directly by physical processes such as grinding, crushing, or woodworking. Solid particles can also be generated in chemical processes, where high temperature processes may lead to the formation of volatile metal particles, particles of metal oxides, or other

materials. Incomplete combustion leads to the emission of solid particles of carbon or particles from the unburnable minerals in the fuel.

Liquid particles can be generated by condensation processes or through chemical reaction. The blue haze seen from some process stacks is due to the presence of condensed organic materials in the exhaust gases. Acid gases, such as sulfur trioxide (SO_3) can condense and form droplets of sulfuric acid (H_2SO_4) "aerosol." The formation of liquid particles is generally quite temperature dependent. In many cases, they may not be formed until the flue gas is emitted from the stack. Water vapor can condense and form droplets, which may effectively scatter light to exhibit the "steam plume" commonly observed from power plants on cold, winter days. However, in most cases, water is not considered as a pollutant, and is excluded from regulatory definitions of particulate matter.

But in this discussion, you might have noticed that we are raising a question: If particle formation is dependent on temperature and we don't count water droplets, what is "particulate matter"? The U.S. Environmental Protection Agency responds as follows. **Particulate matter** is any finely divided solid or liquid material, other than uncombined water, as measured by the reference methods (EPA, 1992).

In other words, the reference methods define what our particulate matter is. In the reference methods, the temperature at which the particles are to be collected is defined, and water is collected and measured separately. By specifying how the particles are to be collected, we are defining what our particulate matter is. This may in fact be a regulatory expedience, but the definition has worked well in the regulatory process of measuring and controlling flue gas emissions of particulate matter.

Particle Size

Another characteristic of particles is their size. In any sample of particles obtained from a flue gas, the particles will have different sizes and shapes. Particles formed by condensation or chemical processes are generally spherical. Particles formed in grinding or crushing operations are usually irregular in shape. The size of a particle is characterized by its diameter. For irregular particles, the **aerodynamic diameter** is used (see Chapter 9).

Particle diameters can typically range from a few hundredths of a micrometer (10^{-6} μm) to a hundred micrometers. In sources where particulate emissions are controlled by baghouses or electrostatic precipitators, particle sizes typically range from 0.1 to 1 μm. Figure 1-1 shows some of the size ranges of particles occurring from natural and manmade processes.

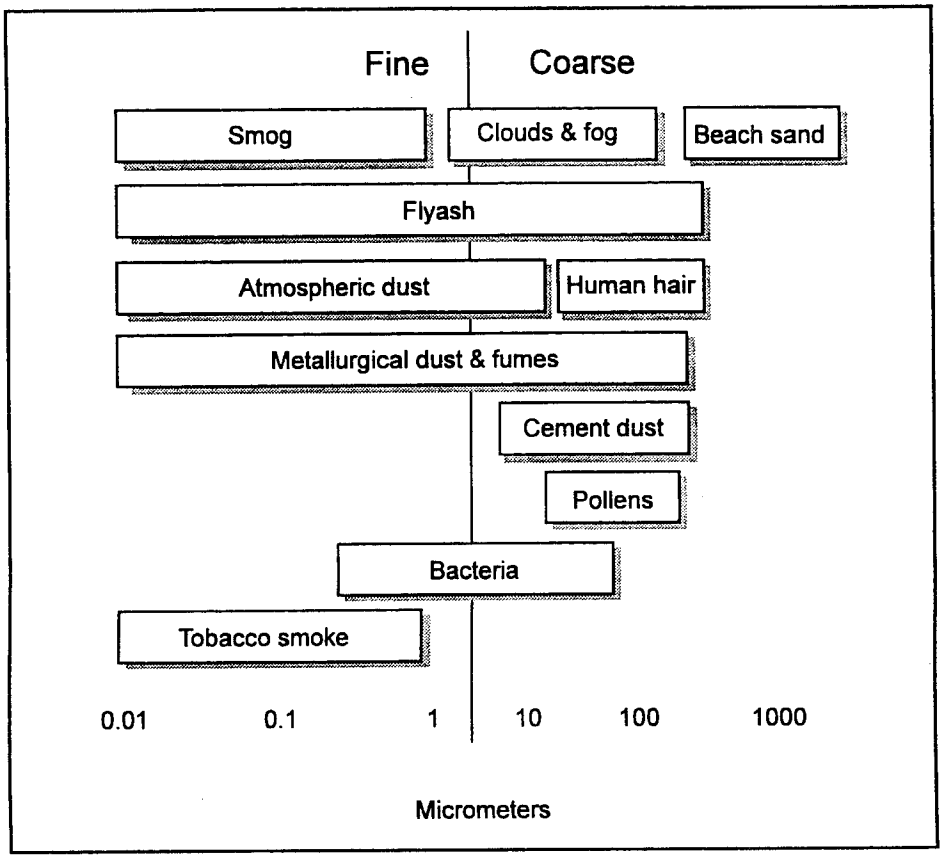

Figure 1-1. Particle size ranges

The size of a particle will influence its behavior. For example, the "large" particles greater than 10 μm are prone to settling, or falling out of the gas stream. These particles are relatively easy to collect and remove. Smaller particles, less than 1 μm in diameter, are more difficult to collect. They can slip through filter pores or diffuse away from water droplets or other collection media.

Health Effects

Particle size also has great implications with regard to human health. Figure 1-2 shows a schematic of the respiratory system and the behavior of particles through the system.

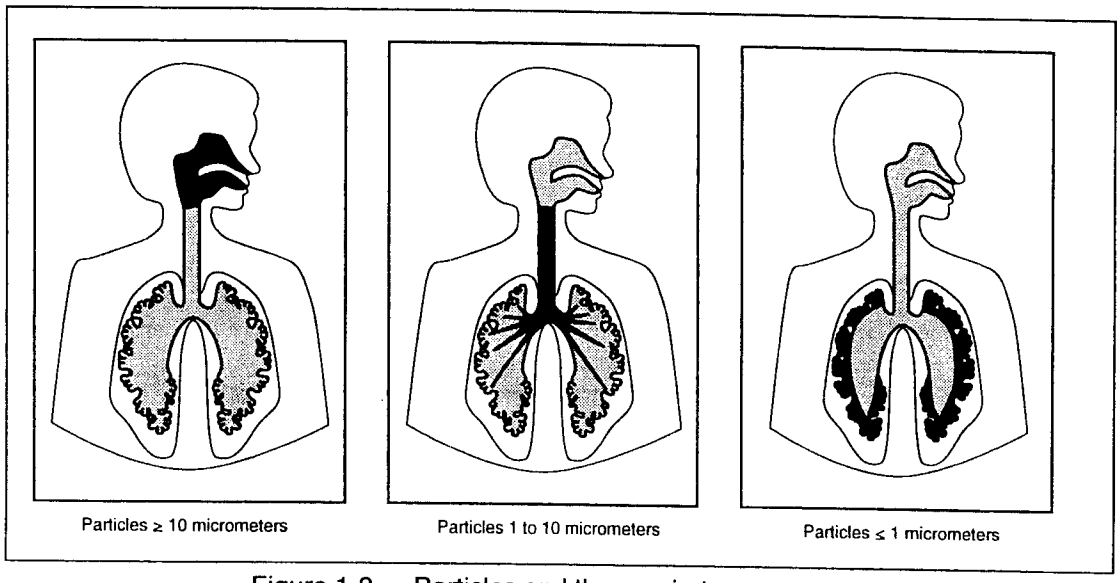

Figure 1-2. Particles and the respiratory system

Particles greater than 10 μm in diameter tend to collect in the upper part of the respiratory system. Here, particles are filtered by nasal hair. The warm, humid conditions of the nasal passages act to remove the particles in the mucous layer lining the nasal cavity and trachea. Particles collect moisture as they move through the upper respiratory region. The resulting larger particles are removed by sneezing and coughing. In addition, fine, hairlike cilia which line the walls of the respiratory system continually move the mucous, where it is removed by swallowing.

Particles in the range of 1 to 10 μm in diameter tend to collect in the middle part of the respiratory system, the tracheobronchial region. Particles in the size range of 1 μm tend to deposit at locations where the bronchi of the lungs begin to branch off into the smaller bronchioles. Here, the particles impact the walls of the bronchi because they can't make the turn into the bronchioles. The smaller, submicron size particles (< 1 μm) can make the turn and penetrate down into the air sacs (the alveoli, where oxygen is transferred to the blood).

Particles with diameters of 0.5 μm in diameter or less float into the air sacs and float out within the next breath or two. Particles with diameters from 0.5 to 1 μm are captured by phagocytes and eliminated through the circulatory system.

The deposition and removal mechanisms for particles obviously depend on the size of the particles. Figure 1-3 shows the fraction of particles deposited in the three areas of the respiratory system.

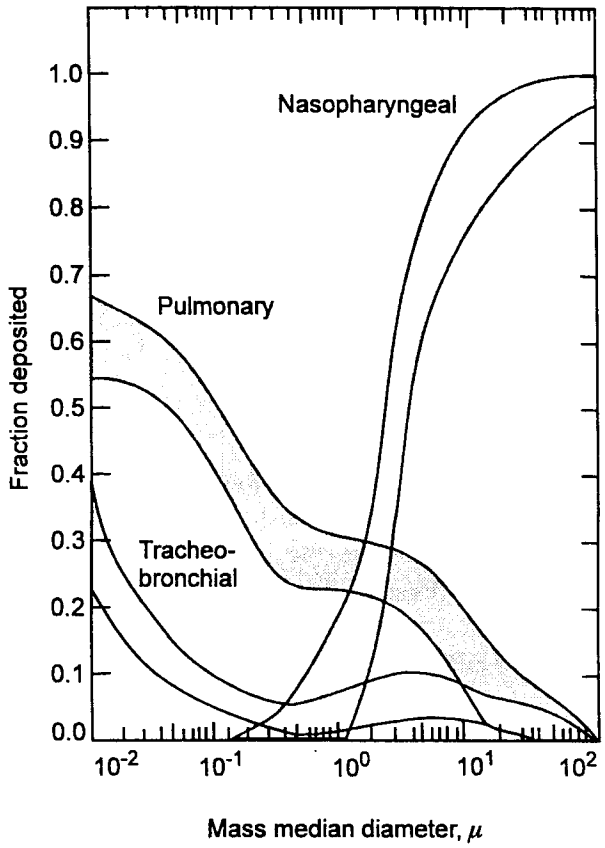

Figure 1-3. Particle deposition in the respiratory system

Note that particles larger than 10 μm in diameter are deposited in the upper part of the respiratory system, where they are easily removed by physiological processes. The action of cilia and respiration act to remove smaller size particles in the bronchi and alveoli. Although the respiratory system can clean itself, continuous exposure to high levels of particulate matter can overwhelm the cleaning mechanisms and may cause the cilia to stop beating or fibrous tissue to develop in the alveoli. This of course leads to debilitating lung diseases.

Also, if soluble liquid particles or solid particles are deposited in the respiratory system, they can be readily absorbed into the tissues. Acid and radioactive materials (such as the radon "daughters" found in buildings with radon accumulation problems) obviously can cause irritation or more serious damage.

PM_{10} Standards

Recognizing the relationship between particle size and deposition within the respiratory system, the EPA revised the National Ambient Air Quality primary and secondary standards for suspended particulate matter on July 31, 1987 (EPA, 1987). The standards limit the concentration of suspended particulate matter in the atmosphere to 150 μg/m³ for any 24-hr period (primary standard) during the year and, 50 μg/m³ for the annual arithmetic mean (secondary standard).

This standard is determined for suspended particles of only 10 μm or less. That is, for an air quality control region to meet the standard, the particulate matter suspended in the atmosphere is measured so as to exclude particles larger than 10 μm in diameter (aerodynamic diameter). Ambient air measurement devices must therefore be capable of measuring all particles less than or equal to 10 μm in diameter.

This cut-off point of 10 μm has of course affected source emission measurement methods. In Methods 5 and 17, (EPA, 1993), particles of all sizes are caught on a particulate filter. Two additional methods have been subsequently developed to measure particulate matter of 10 μm and under. These methods are Method 201, the Exhaust Gas Recycle (EGR) procedure and Method 201A, the Constant Sampling Rate (CSR) procedure. It has been recommended that the states use these methods to meet their source surveillance requirements.

Emission Sources

Source sampling is the set of procedures used to obtain samples of flue gases from stationary sources. These flue gases may contain products of combustion such as carbon dioxide and water, pollutant gases such as sulfur dioxide, nitric oxides, carbon monoxide, organic compounds, "air toxics," and particulate matter. Emissions depend upon the type of emission source. Therefore, a source tester must choose the proper sampling techniques to obtain representative samples of gases and particulate matter.

Typical Emission Sources

Emission sources commonly sampled are coal- and oil-fired power plants, municipal and hazardous waste incinerators, paper pulp mills, asphalt batch plants, cement plants, and other process industry plants.

Particles are emitted by most combustion sources. For example, in the non-nuclear electric utilities, steam and electric power are produced by burning fossil fuels such as oil and coal. Materials in the fuel that don't burn, such as silica, or unburned carbon (soot) can be emitted into the atmosphere if not collected by some air pollution control device. Because coal has a higher ash content than oil or gas, coal-fired plants have the potential to emit relatively higher amounts of particulate matter. Particulate emissions from gas-fired combustion sources are generally negligible.

But even within a given source category, such as a coal-fired power plant (Figure 1-4), other variables will affect the level of particulate emissions. For example, particulate emissions can be higher from pulverized coal boilers than from cyclone-fired or spreader stoker-fired boilers. For oil-fired plants as well as coal-fired plants, the poorer the grade of fuel, the higher the particulate emissions. Particulate emissions from the #5 and #6 fuel oils will be higher than those from the lighter distillates (e.g., #2).

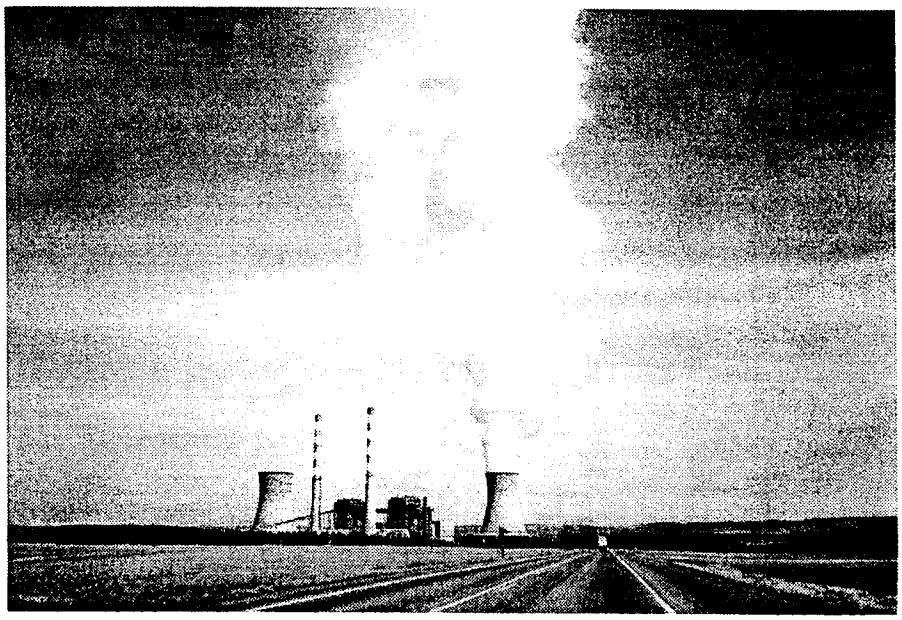

Figure 1-4. Coal-fired power plant

Municipal and hazardous waste incinerators burn a wide variety of fuels (Figure 1-5). Particulate emissions here are very dependent upon the incinerator design and on how the plant is operated. In this regard, the combustion airflow rate is very important. If there is too much air, the temperature and residence time will decrease, resulting in poor combustion. In addition, unburned materials can be swept up into the exhaust gas stream. If there is too little air, combustion will be poor and unburned particles will also be incorporated into the exhaust gas. These facilities are highly regulated, with emission standards being frequently more stringent than for other sources.

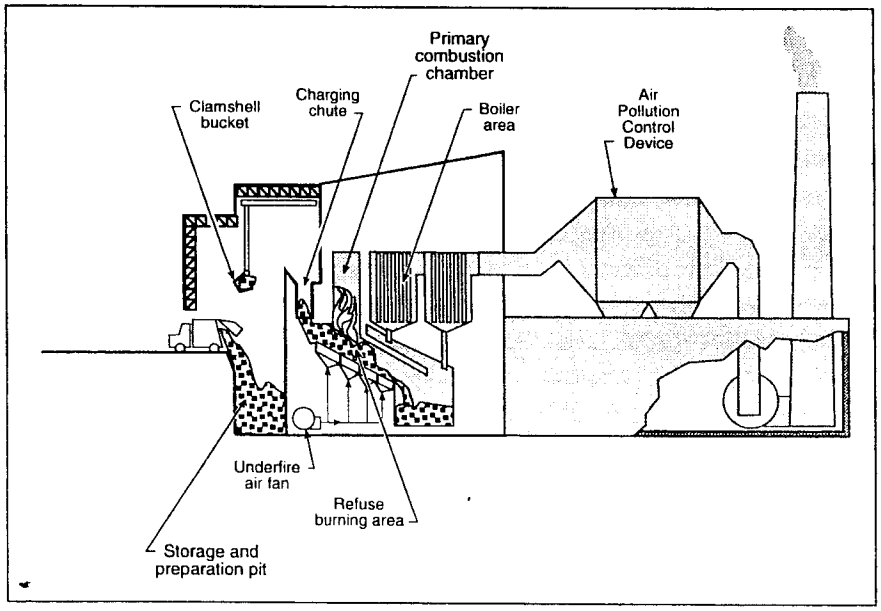

Figure 1-5. Schematic of a municipal incinerator

In the process industries, particulate emissions can occur from a number of points in the plant operations. In contrast to sampling from a single stack or duct, sampling may be required at different facilities within the source. For example, in a cement plant, particulate emissions are sampled from the kiln exhaust and clinker cooler. In kraft pulp mills (Figure 1-6), particulate emissions are sampled from the kraft recovery furnace, smelt dissolving tank, and lime kiln.

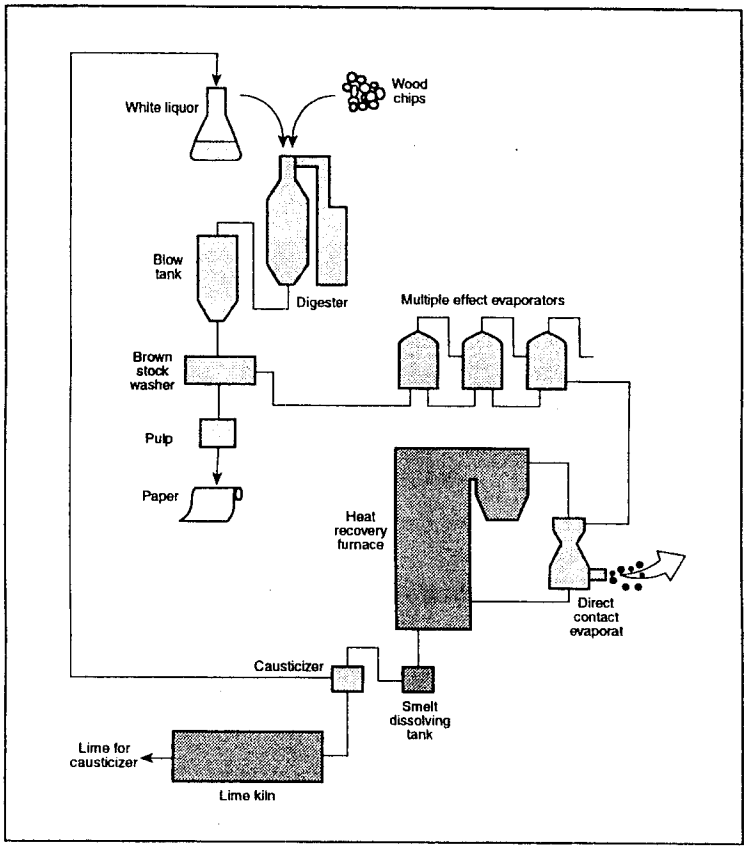

Figure 1-6. Schematic of the kraft pulping process

Of course, the emission of particulate matter is regulated. Industries are required to control the emission of particles into the atmosphere; otherwise the ambient air standards could not be met. Various devices are used to control particulate emissions, including electrostatic precipitators, baghouses, and wet scrubbers. These devices may work better in some applications than in others, and one of the jobs of source testing is to see how well the devices work. By testing before and after the control equipment, the source tester can determine its removal efficiency for particulate matter. This number (which can be better than 99%) can then be used to verify the guarantees of the control equipment manufacturer or to meet efficiencies mandated by the regulatory agency.

Emission Standards

Emission standards for stationary sources are established by both the U.S. EPA and the states. The U.S. EPA promulgates engineering-based standards for "new" sources, whereas the states establish standards for "existing" sources so that *ambient* air quality standards can be met or attained.

Existing sources are those constructed before the U.S. EPA proposed standards for a new source category. The EPA standards are known as the "New Source Performance Standards" or NSPS, and are found in Title 40, Part 60 of the Code of Federal Regulations (CFR). Title 40 addresses the U.S. EPA environmental regulations, and Part 60 includes the requirements for new stationary sources (referred to as 40 CFR 60). Part 60 is further divided into subparts, and each stationary source category is assigned a subpart. These are listed in Table 1-1.

Table 1-1. New Source Performance Standards (NSPS) 40 CFR 60 Subparts

Subpart Letter	Source Category
D	Fossil-Fuel Fired Steam Generators (Built after August 17,1971)
D_a	Electric Utility Steam Generating Units (Built after September 18, 1978)
D_b	Industrial-Commercial-Institutional Steam Generating Units
D_c	Small Industrial-Commercial-Institutional Steam Generating Units
E	Incinerators
E_a	Municipal Waste Combustors (Built after December 20, 1989)
F	Portland Cement Plants
G	Nitric Acid Plants
H	Sulfuric Acid Plants
I	Asphalt Concrete Plants
J	Petroleum Refineries
K	Storage Vessels for Petroleum Liquids (Constructed after June 11, 1973)
K_a	Storage Vessels for Petroleum Liquids (Constructed after May 18, 1978)
K_b	Storage Vessels for VOCs (post 7/23/84)
L	Secondary Lead Smelters
M	Secondary Brass and Bronze Ingot Production
N	Primary Emissions from Basic Oxygen Process Furnaces (post 6/11/73)
N_a	Secondary Emissions from Basic Oxygen Process Furnaces (post 1/20/83)
O	Sewage Treatment Plants
P	Primary Copper Smelters
Q	Primary Zinc Smelters
R	Primary Lead Smelters
S	Primary Aluminum Reduction Plants
T	Phosphate Fertilizer Industry: Wet Process Phosphoric Acid Plants
U	Phosphate Fertilizer Industry: Superphosphoric Acid Plants
V	Phosphate Fertilizer Industry: Diammonium Phosphate Plants
W	Phosphate Fertilizer Industry: Triple Superphosphate Plants
X	Phosphate Fertilizer Industry: Granular Triple Superphosphate Storage
Y	Coal Preparation Plants
Z	Ferroalloy Production Facilities
AA	Steel Plants - Electric Arc Furnaces
AA_a	Steel Plants: Electric Arc Furnaces, Argon-Oxygen Decarburization Vessels (post 8/17/83)
BB	Kraft Pulp Mills
CC	Glass Manufacturing Plants

Table 1-1. New Source Performance Standards (NSPS) 40 CFR 60 Subparts

Subpart Letter	Source Category
DD	Grain Elevators
EE	Surface Coating of Metal Furniture
GG	Stationary Gas Turbines
HH	Lime Plants
KK	Lead-Acid Battery Manufacture Plants
LL	Metallic Mineral Processing Plants
MM	Automobile and Light-Duty Truck Surface Coating Operations
NN	Phosphate Rock Plants
PP	Ammonium Sulfate Manufacture Plants
QQ	Graphic Art Industry Publication Rotogravure Printing
RR	Pressure Sensitive Tape and Label Surface Coating Operations
SS	Industrial Surface Coating: Large Appliances
TT	Metal Coil Surface Coating
UU	Asphalt Processing and Asphalt Roofing Manufacture
VV	Equipment Leaks of Volatile Organic Compounds (VOC) in Synthetic Organic Chemical Manufacturing Industry
WW	Beverage Can Surface Coating Industry
XX	Bulk Gasoline Terminals
AAA	New Residential Wood Heaters
BBB	Rubber Tire Manufacturing
DDD	Polymer Manufacturing
FFF	Flexible Vinyl and Urethane Coating and Printing
GGG	Equipment Leaks of VOC in Petroleum Refineries
HHH	Synthetic Fiber Production Facilities
III	Synthetic Organic Chemical Manufacturing Industry (SOCMI) Air Oxidation Units
JJJ	Petroleum Dry Cleaners
KKK	Equipment Leaks of VOC from Onshore Natural Gas Processing Plants
LLL	Onshore Natural Gas Processing Plants: SO_2 Emissions
NNN	SOCMI Distillation Operations
OOO	Nonmetallic Mineral Processing Plants
PPP	Wool Fiberglass Insulation Manufacturing Plants
QQQ	Petroleum Refinery Wastewater Systems
SSS	Magnetic Tape Coating Facilities
TTT	Surface Coating Plastic Business Machine Parts
UUU	Calciners and Dryers in Mineral Industries
VVV	Polymeric Coating of Supporting Substrates

Note from Table 1-1 that the NSPS standards are expressed in different forms, such as concentration (gr/dscf), mass rate (lb/hr), or in terms of product produced (lb/10^6 Btu, lb/ton). The methods of calculating these parameters are relatively straightforward and will be discussed later in this manual.

State requirements can be found in state environmental regulations and, more specifically, in source operating permits. The states must also meet certain requirements specified by the U.S

EPA in 40 CFR 51. Each state must develop a State Implementation Plan (SIP) detailing how it will meet ambient air quality standards.

It should also be noted that the Code of Federal Regulations is continually changing. Old requirements may be revised or new standards may be incorporated. Such changes first appear as proposals in the Federal Register (FR), a daily government publication. After public discussion and comment, the proposed rules are revised and published in the Federal Register. The final rules are then incorporated in the next issue of the Code of Federal Regulations.

So, let us return to particulate emission standards. For new sources, these are found in the CFR subparts. Current NSPS particulate emission standards are given in Table 1-2.

Table 1-2. New Source Performance Standards for Particulate Emissions 40 CFR 60 Subparts

Subpart Letter	Source Category	Metric Units	English Units
D	Fossil-Fuel Fired Steam Generators	43 ng/J	0.10 lb/10^6 Btu
D_a	Electric Utility Steam Generating Units	13 ng/J	0.03 lb/10^6 Btu
D_b	Industrial-Commercial-Institutional Steam Generating Units	22 ng/J	0.05 lb/10^6 Btu
D_c	Small Industrial-Commercial-InstitutionalSteam Generating Units	22 ng/J 43 ng/J	0.05 lb/10^6 Btu (coal) 0.10 lb/10^6 Btu (coal + other fuels)
E	Incinerators	0.18 g/dscm	0.08 gr/dscf (corr. to 12% CO_2)
E_a	Municipal Waste Combustors (Metals)	34 mg/dscm	0.015 gr/dscf (corr. to 7% O_2)
F	Portland Cement Plants	0.15 kg/ton 0.50 kg/ton	0.30 lb/ton of feed (kiln) 0.10 lb/ton of feed (clinker cooler)
I	Hot Mix Asphalt Plants	90 mg/dscm	0.04 gr/dscf
J	Petroleum Refineries (Incremental Rate)	1.0 kg/10^3 kg 43 g/MJ	1.0 lb/1000 lb of coke burnoff (FCCU) 0.10 lb/10^6 Btu for incineration
L	Secondary Lead Smelters	50 mg/dscm	0.022 gr/dscf
M	Secondary Brass and Bronze Ingot Production	50 mg/dscm	0.022 gr/dscf
N	Basic Oxygen Process Furnaces	50 mg/dscm	0.022 gr/dscf
N_a	Basic Oxygen Process Steel Making Facilities	23 mg/dscm	0.010 gr/dscf
O	Sewage Treatment Plants	0.65 g/kg	1.30 lb/ton dry sludge input
P	Primary Copper Smelters	50 mg/dscm	0.022 gr/dscf
Q	Primary Zinc Smelters	50 mg/dscm	0.022 gr/dscf
R	Primary Lead Smelters	50 mg/dscm	0.022 gr/dscf
S	Primary Aluminum Reduction Plants	1.0 kg/Mg 0.95 kg/Mg 0.05 kg/Mg	2.0 lb/ton Potroom Soderberg Plant (Total F) 1.9 lb/ton Potroom Prebake Plant (Total F) 0.1 lb/ton Anode Bake Plant (Total F)
T	Wet Process Phosphoric Acid Plants	10.0 g/ton	0.020 lb/ton P_2O_5 feed (Total F)
Y	Coal Preparation Plants	0.70 g/dscm	0.031 gr/dscf
Z	Ferroalloy Production Facilities	0.45 kg/MW-hr 0.23 Kg/MW-hr	0.99 lb/MW-hr 0.51 lb/MW-hr
AA	Steel Plants - Electric Arc Furnaces	12 mg/dscm	0.0052 gr/dscf

Table 1-2. New Source Performance Standards for Particulate Emissions 40 CFR 60 Subparts

Subpart Letter	Source Category	Metric Units	English Units
BB	Kraft Pulp Mills	0.10 g/dscm 0.10 g/kg 0.15 g/dscm 0.39 g/dscm	0.044 gr/dscf (corr. 8% O_2) Recov. Furnace 0.2 lb/ton black liq. solids smelt tank 0.067 gr/dscf (corr. 10% O_2) lime kiln (gas) 0.13 gr/dscf (corr. 10% O_2) lime kiln (liq. fuel)
CC	Glass Manufacturing Plants	0.1 - 0.5 g/kg glass produced 0.5 - 1.0 g/kg glass produced (modified furnaces)	
DD	Grain Elevators	0.023 g/dscm	0.01 gr/dscf
HH	Lime Plants	0.30 kg/mg	0.60 lb/ton
KK	Lead Acid Battery Manufacturing Plants	0.40 mg/dscm 1.0 mg/dscm 1.0 mg/dscm 5.0 mg/kg 1.00 mg/dscm	0.0001766 gr/dscf (grid casting facility) 0.00044 gr/dscf (paste mixing) 0.00044 gr/dscf (three process operations) 0.010 lb/ton feed (lead oxide manuf. facility) 0.00044 gr/dscf (any gases)
LL	Metallic Mineral Processing Plants	0.05 g/dscm	
NN	Phosphate Rock Plants	0.030 kg/Mg 0.12 kg/Mg 0.055 kg/Mg 0.006 kg/Mg	0.06 lb/ton feed (rock dryer) 0.23 lb/ton (calciner processing) 0.11 lb/ton 0.012 lb/ton feed (grinder)
PP	Ammonium Sulfate Manufacturing Plants	0.15 kg/Mg	0.30 lb/ton ammonium sulfate produced
VV	Asphalt Processing and Asphalt Roofing Manufacture	0.04 kg/Mg asphalt shingle 0.40 kg/Mg saturated felt	
AAA	New Residential Wood Heaters	4.1 g/hr (with catalytic converter) 7.5 g/hr (without catalytic converter)	
OOO	Nonmetallic Mineral Processing Plants	0.05 g/dscm	
PPP	Wool Fiberglass Insulation Manufacturing Plants	5.5 kg/Mg	11.0 lb/ton

The EPA Source Testing Reference Methods

The source tester extracts samples from a stack or duct and analyzes the samples to determine the levels of particulate matter and gases emitted. The source tester frequently works on platforms 200 to 300 feet up the stack, on catwalks beside ductwork, or in the annular spacing between the stack liner and stack. The work is often exciting (one goes to high places quickly in this business), grueling, tedious, and sometimes dangerous. But it does require a technical knowledge of source operations and testing methods, in addition to a lot of common sense.

The testing methods are defined and standardized for different source categories. Each source is somewhat different. Sampling situations can be difficult—attempting to obtain a representative flue gas sample on an exposed platform during the heat of summer or cold of winter is not the same as performing a test in a laboratory. As a result of realities such as this, the source test methods have been developed in order that samples can be obtained in a reasonable length of time, at relatively reasonable cost, without sacrificing their technical viability.

Accuracy in source testing is somewhat hard to define. No one can actually know the *true* value of an emission parameter. We could perhaps collect all the flue gas emitted from a stack and weigh all the particulate matter found, but this is certainly not practical. Instead, test methods are developed, evaluated, checked, and cross-checked with other methods and data to validate their use. Collaborative tests conducted by teams of source testers help to establish the test method precision. In the end, the test methods do incorporate practical compromises, but once promulgated by regulation, they become the *reference method* to which other data is to be compared, such as engineering data or continuous emission monitoring (CEM) data.

Reference methods for new stationary sources are found in Appendix A of 40 CFR 60. The states use these methods in both federal and state programs. The following methods have been promulgated.

Table 1-3. US EPA Reference Methods of 40 CFR 60 Appendix A

APPENDIXES TO PART 60

APPENDIX A—TEST METHODS

Method 1—Sample and velocity traverses for stationary sources
Method 1A—Sample and velocity traverses for stationary sources with small stacks or ducts
Method 2—Determination of stack gas velocity and volumetric flow rate (Type S pitot tube)
Method 2A—Direct measurement of gas volume through pipes and small ducts
Method 2B—Determination of exhaust gas volume flow rate from gasoline vapor incinerators
Method 2C—Determination of stack gas velocity and volumetric flow rate in small stacks or ducts (standard pitot tube)
Method 2D—Measurement of gas volumetric flow rates in small pipes and ducts
Method 3—Gas analysis for carbon dioxide, oxygen excess air, and dry molecular weight
Method 3A—Determination of oxygen and Carbon Dioxide Concentrations in Emissions From Stationary Sources (Instrumental Analyzer Procedure)
Method 4—Determination of moisture content in stack gases
Method 5—Determination of particulate emissions from stationary sources
Method 5A—Determination of particulate emissions from the asphalt processing and asphalt roofing industry
Method 5B—Determination of nonsulfuric acid particulate matter from stationary sources
Method 5C [Reserved]
Method 5D—Determination of particulate emissions from positive pressure fabric filters
Method 5E—Determination of particulate emissions from the wool fiberglass insulation manufacturing industry
Method 5F—Determination of nonsulfate particulate matter from stationary sources
Method 5G—Determination of particulate emissions from wood heaters from a dilution tunnel sampling location
Method 5H—Determination of particulate emissions from wood heaters from a stack location
Method 6—Determination of sulfur dioxide emissions from stationary sources
Method 6A—Determination of sulfur dioxide, moisture, and carbon dioxide emissions from fossil fuel combustion sources
Method 6B—Determination of sulfur dioxide and carbon dioxide daily average emission from fossil fuel combustion source

Table 1-3. US EPA Reference Methods of 40 CFR 60 Appendix A (continued)

Method 6C—Determination of sulfur dioxide emission from stationary sources (instrumental analyzer procedure)
Method 7—Determination of nitrogen oxide emissions from stationary sources
Method 7A—Determination of nitrogen oxide emissions from stationary sources-Ion chromatographic method
Method 7B—Determination of nitrogen oxide emissions from stationary sources (Ultraviolet spectrophotometry)
Method 7C—Determination of nitrogen oxide emissions from stationary sources-Alkaline-permanganate/ colorimetric method
Method 7D—Determination of nitrogen oxide emissions, from stationary sources—Alkaline - permanganate/ion chromatographic method
Method 7E—Determination of nitrogen oxides emissions from stationary sources (instrumental analyzer procedure)
Method 8—Determination of sulfuric acid mist and sulfur dioxide emissions from stationary sources
Method 9—Visual determination of the opacity of emissions from stationary sources
Alternate method I—Determination of the opacity of emissions from stationary sources remotely by lidar
Method 10—Determination of carbon monoxide emissions from stationary sources
Method 10A—Determination of carbon monoxide emissions in certifying continuous emissions monitoring systems at petroleum refineries
Method 10B—Determination of carbon monoxide emissions from stationary sources
Method 11—Determination of hydrogen sulfide content of fuel gas streams in petroleum refineries
Method 12—Determination of inorganic lead emissions from stationary sources
Method 13A—Determination of total fluoride emissions from stationary sources—SPADNS zirconium lake method
Method 13B—Determination of total fluoride emissions from stationary sources—Specific ion electrode method
Method 14—Determination of fluoride emissions from potroom roof monitors for primary aluminum plants
Method 15—Determination of hydrogen sulfide, carbonyl sulfide, and carbon disulfide emissions from stationary sources
Method 15A—Determination of total reduced sulfur emissions from sulfur recovery plants in petroleum refineries
Method 16—Semicontinuous determination of sulfur emissions from stationary sources
Method 16A—Determination of total reduced sulfur emissions from stationary sources (impinger technique)
Method 16B—Determination of total reduced sulfur emissions from stationary sources
Method 17—Determination of particulate emissions from stationary sources (in- stack filtration method)
Method 18—Measurement of gaseous or organic compound emissions by gas chromatography
Method 19—Determination of sulfur dioxide removal efficiency and particulate, sulfur dioxide and nitrogen oxides emission rates
Method 20—Determination of nitrogen oxides, sulfur dioxide, and diluent emissions from stationary gas turbines
Method 21—Determination of volatile organic compound leaks
Method 22—Visual determination of fugitive emissions from material sources and smoke emissions from flares
Method 23—Determination of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans from stationary sources
Method 24—Determination of volatile matter content, water content, density, volume solids, and weight solids of surface coatings
Method 24A—Determination of volatile matter content and density of printing inks and related coatings
Method 25—Determination of total gaseous nonmethane organic emissions as carbon
Method 25A—Determination of total gaseous organic concentration using a flame ionization analyzer
Method 25B—Determination of total gaseous organic concentration using a non-dispersive infrared analyzer
Method 26—Determination of hydrogen chloride emissions from stationary sources
Method 27—Determination of vapor tightness of gasoline delivery tank using pressure-vacuum test
Method 28—Certification and auditing of wood heaters
Method 28A—Measurement of air to fuel ratio and minimum achievable burn rates for wood-fired appliances

In this manual on particulate sampling, we will discuss the first five methods in detail:

Method 1 - Sample and velocity traverses for stationary sources

Method 2 - Determination of stack gas velocity and volumetric flow rate (Type S pitot tube)

Method 3 - Gas analysis for carbon dioxide, oxygen, excess air, and dry molecular weight

Method 4 - Determination of moisture content in stack gases

Method 5 - Determination of particulate emissions from stationary sources

Methods 8, 13, and 17 are also used to collect particulate matter and incorporate modifications of the isokinetic sampling apparatus of Method 5. These methods indirectly define the flue gas particulate matter by specifying how the gas is to be sampled. These methods will be addressed further in Chapter 8 when we discuss the definition of particulate matter. The test methods for pollutant gases, which comprise the remainder of the methods, are quite diverse and are applied for specified source categories. These will not be discussed here, since they are the subject of another topic: gas sampling and analysis.

Other particulate sampling methods are found in 40 CFR 51 Appendix M, as part of the "tool box" of methods that the states may use in implementing their programs. Both Method 201, the exhaust gas recycle (EGR) method and Method 201A, the constant sampling rate (CSR) procedure, for the determination of PM_{10} can be found here.

As a final note, it should be recognized that other countries have developed and standardized their own test methods. In many cases they differ significantly from the U.S. test methods. The fact that more than one method has been used for the same measurement raises the question as to which is better, or which one will more closely obtain the "true value." The answer to the question may never be known, but as long as *one* method is used consistently within a state or country, the data obtained will be consistent relative to the method established as a reference.

The International Standards Organization (ISO) is striving to obtain a wider, worldwide consistency by establishing international methods. This organization evaluates the different national methods and, by consensus, establishes a consistent set of procedures that can be used for national standards. Significantly the European Community will be using the ISO methods in the future so that data obtained will be comparable between the member countries. The ISO method for particulate sampling from stationary sources is ISO 9096, "Determination of Concentration and Mass Flow Rate of Particulate Material in Gas-carrying Ducts - Manual Gravimetric Method."

Source testing methods are becoming more refined and standardized. In most cases, current source test methods can meet the present demands of regulatory agencies for representative and accurate data. However, with increasingly strict emission limitations, new challenges in testing arise. Changes in source test methods are becoming necessary in order to improve the accuracy of measurements at very low particulate emission levels. In addition, developments will be necessary for particle size measurements, continuous particulate measurements, and particle identification. In the future, as regulatory demands evolve, it is anticipated that source test methods will also evolve to meet the demands.

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Chapter 2

The Properties of Gases

Source testing deals with gases. During the source test, a sample is extracted from a stack or duct into a source test apparatus. This apparatus does a number of things to the sample: it removes particulate matter from the gas, it cools the gas down, and it condenses out any water contained in the gas. Of course, these various processes change the character of the gas sample. The sample volume changes, the gas temperature changes, and the composition changes. These changes must all be accounted for in our source test calculations.

So, in order to understand source testing, we must first understand how gases behave. We already understand much of this intuitively, but source testing is a quantitative discipline and we must be able to calculate exactly how a sampling apparatus will affect a gas sample.

Gas Volume

Gas volume is dependent upon three variables:

1. Amount of gas (composition)
2. Temperature
3. Pressure

These variables all have an effect on a volume of a sample gas. The resultant effect can be determined by using an expression called the **ideal gas law.** The discussion given here will help give an understanding of this law and how we can use it in our source test calculations.

Composition

If we blow up a balloon, it will expand. It will become larger as we blow more air into it. The gas in the balloon will be principally composed of oxygen, nitrogen, carbon dioxide, water vapor, and small amounts of other molecules in a gaseous state. As long as the molecules are in a gaseous state, the size of the balloon will be dependent upon the number of molecules in the balloon (Figure 2-1).

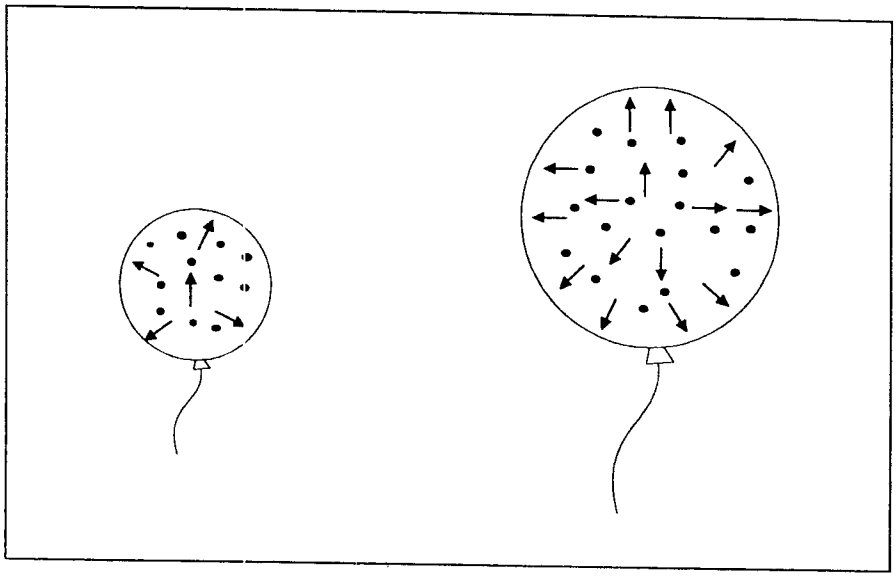

Figure 2-1. The volume of a balloon is dependent upon the quantity of air blown into it.

In 1811, the Italian physicist, Amadeus Avogadro, found that equal volumes of gas contain the same number of molecules at the same temperature and pressure. It was later determined that 1 cm^3 of gas contains 2.71×10^{19} atoms or molecules at 0° C and 1 atmosphere of pressure. A more common expression of this fact is that:

> 22.4 liters of gas at 0° C and 1 atmosphere of pressure contain 6.023×10^{23} atoms (or molecules).

The number 6.023×10^{23} is known as **Avogadro's number** and is a very important number used in chemical calculations. Let us see why this should be important. First, consider that every atom has an atomic weight and every molecule has a molecular weight. The molecular weights for molecules found in flue gases are given in Table 2-1.

Table 2-1. Molecular Weights of Common Stack Gas Constituents

Molecule	Symbol	Molecular Weight
Oxygen	O_2	32
Nitrogen	N_2	28
Water	H_2O	18
Carbon Dioxide	CO_2	44
Carbon Monoxide	CO	28
Sulfur Dioxide	SO_2	64
Nitric Oxide	NO	30

Basically, the molecular weights have been obtained by assigning an atomic weight of 12 to the carbon atom and then expressing all other atomic and molecular weights to the atomic weight of carbon as a standard. In other words, a sulfur dioxide molecule is 64/12 or 5.33 times as heavy as a carbon atom, or a water molecule is only 18/12 or 1.5 times as heavy as a carbon atom.

But now, let us go one step further. Let us express the molecular weight in grams. If we have 12 grams of carbon, it has been found that 6.023×10^{23} carbon atoms are in that 12 grams. If we have 18 grams of water, we still have 6.023×10^{23} or Avogadro's number of molecules. Since the water molecule is 1.5 times as heavy as the carbon atom, the number of molecules needed to make up 18 grams of water should be the same as the number of atoms needed to make up 12 grams of carbon. In fact, for any molecule, if you write its molecular weight in grams, an Avogadro's number worth of molecules will be in that number of grams. This number of grams is known as the **gram-molecular weight** or one **mole**. In other words, one mole of a substance is the mass of the substance that contains Avogadro's number of molecules and which is equivalent to its molecular weight expressed in grams.

The symbol used in chemistry and in source test calculations for the number of moles of a gas is n. To find the number of moles in a given quantity of material, one divides by the gram-molecular weight:

$$n = (\text{grams of material})/MW \qquad (2\text{-}1)$$

Where: MW = the molecular weight expressed as g/g-mole

The number of moles can also be calculated using English units as follows:

$$n = (\text{pounds of material})/M \qquad (2\text{-}2)$$

Where: M = the molecular weight expressed as lb/lb-mole

(*Note*: In stack sampling, most gases tested are a mixture of a number of gases. But if you have such a mixture of different gases, each with its own molecular weight, what value of the molecular weight do you use in the Ideal Gas Law calculations? For such calculations, we use the apparent molecular weight of the mixture, M_{mix}:

$$M_{mix} = B_1M_1 + B_2M_2 + B_3M_3 + \cdots = \Sigma B_iM_i \qquad (2\text{-}3)$$

Where: M_{mix}= the apparent molecular weight of the gas mixture

B_i = the mole fraction or proportion by volume of the i^{th} gas component

M_i = the molecular weight of the i^{th} gas component

Now, let us return to our balloon. We understand almost intuitively that the more air we blow into the balloon, the larger its volume will be. Let us say that we are filling a balloon with nitrogen. If we put in two moles of nitrogen, the volume will be twice as large than if we put in only one mole of nitrogen. If we put in one mole of oxygen and one mole of nitrogen, the volume will be again twice that of one mole of nitrogen. If we put in one mole of nitrogen, one

mole of oxygen, and one mole of water vapor, the volume is three times larger. We can keep going on with this. However, if we put the balloon into a freezer and change the water vapor to ice, the water is no longer a gas and the volume will be approximately 2/3 of what it was before.

This can be expressed mathematically as Avogadro's law:

$$V = (\text{constant})\, n \tag{2-4}$$

Where: V = the volume of gas at fixed temperature and pressure

Something similar happens in an EPA Method 5 sampling train. In source testing, we extract a sample and cool it down in an ice bath before we measure the volume of gas collected. The ice bath reduces the number of moles of gas in the sample (we condensed the water), giving us a *dry* gas instead of a *wet* gas. The volume, of course, becomes correspondingly smaller.

Temperature

In addition to the condensation effects discussed previously, temperature has another effect on the volume of our balloon. If the temperature increases, the volume increases. If the temperature decreases, the volume decreases. It has been found that for each 1° C increase in temperature, the gas volume will increase by a factor of 1/273.16 (or 0.366%), or, upon cooling, the gas volume will decrease by a factor of 1/273.16. (*Note*: In English units, the volume change for each °F is 1/491.67.)

We must be careful here, however, since from 0°C, we can't decrease the temperature by more than 273.16 °C or we would get a negative volume. This, of course, defines absolute zero, the limit to which an ideal gas can be cooled. In scientific and engineering calculations, temperature is frequently expressed on the **absolute temperature scale** in terms of degrees **Kelvin** (International System or SI units) or degrees **Rankine** (English units). The conversion between the centigrade scale and the Kelvin scale is as follows:

$$°K = 273.16 + °C \tag{2-5}$$

The conversion between the Fahrenheit scale and the Rankine scale is as follows:

$$°R = 459.67 + °F \tag{2-6}$$

In the United States, the Rankine scale is generally used in source sampling calculations. In this manual and in the EPA methods of 40 CFR 60, the uppercase symbol T is used to denote an absolute temperature, and the lower case t is used to denote degrees Fahrenheit or degrees centigrade. The conversion formulas between the centigrade and Fahrenheit scales are as follows:

$$°F = 1.8°C + 32 \tag{2-7}$$

$$°C = \frac{9}{5}(°F - 32) \tag{2-8}$$

This discussion leads of course to the fact that gas volume changes linearly with respect to the absolute temperature, T (Figure 2-2).

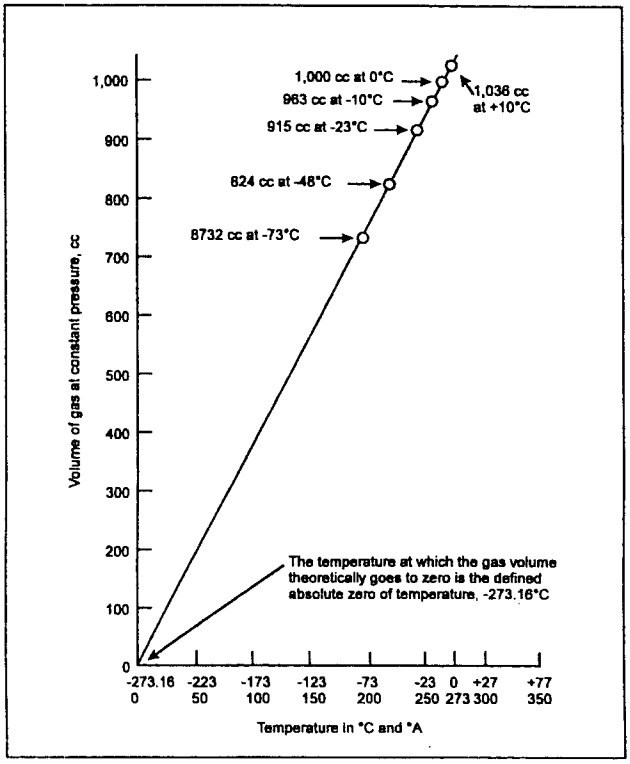

Figure 2-2. Volume of a gas as a function of absolute temperature

This can be expressed mathematically as:

$$V = (\text{constant}) \times T \tag{2-9}$$

If we know the volume of a given amount of gas at one temperature, the volume can be determined at another temperature by the following expression:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \tag{2-10}$$

or,

$$V_2 = \frac{T_2}{T_1} V_1 \tag{2-11}$$

where the subscript 1 refers to the original conditions and the subscript 2 refers to the new conditions. Variations of Eq. 2-10 are used frequently in source test calculations.

Pressure

Gaseous atoms and molecules are continuously moving in space. They move in a random motion, colliding with one another or with the walls of any confining container. The velocity of the molecules or atoms is dependent on their temperature. At very low temperatures, they move slowly; at higher temperatures, they move more rapidly.

If we confine a large number of molecules in a container such as our balloon, they will exert a force on the balloon wall. The molecules are moving randomly, but a certain percentage will hit the wall at any given time. The gas pressure on the wall is then the force exerted by the gaseous atoms or molecules, measured per unit area of the wall surface. This force per unit area can be expressed in units of lb/in.^{2} (psi) or in the metric units of Newtons/m^2 (pascals).

But here, we must first consider the pressure of the atmosphere and its effect on the measurements that we make in source testing. An ocean of air exists above us, extending from the troposphere past the stratosphere. The air exerts a pressure on us and our test apparatus, just as water in the ocean exerts a pressure on the diver. The deeper the diver goes, the greater the pressure.

It has been found that at sea level, the pressure of the air, the gas molecules bombarding us and our test apparatus are 14.7 lb/in.^{2} Looking at this in another way, if we seal off a glass tube, fill it with mercury and then invert it in a pool of mercury (Figure 2-3), the column of mercury will fall until its upper end is exactly 76 cm (760 mm) (under standard conditions) above the level of the mercury pool.

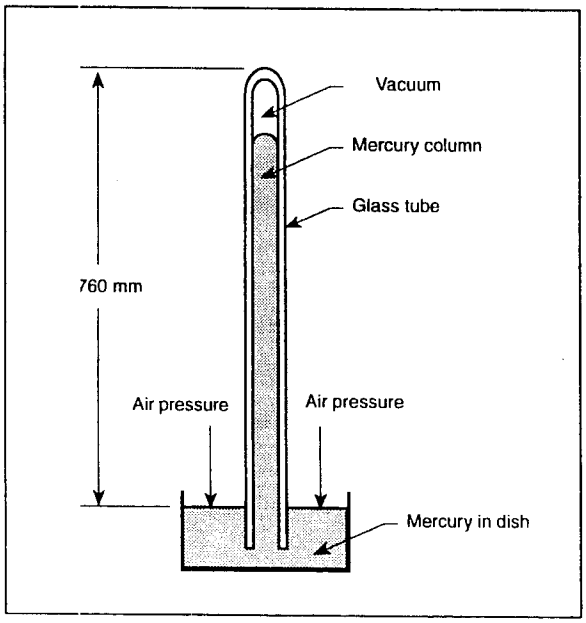

Figure 2-3. A mercury column supported by normal atmospheric pressure

Here the pressure of the atmosphere is forcing the column of mercury up into the tube. One can say that the force exerted by a 76 cm column of mercury is equal to the pressure of the

atmosphere. Mercury columns such as this are called **barometers** and are commonly used to measure atmospheric pressure.

One atmosphere of pressure is therefore defined as the force exerted by a 760 mm column of mercury on an area of 1 cm^2 at 15°C at sea level and at 45° north latitude. In English units, it is equivalent to a pressure of 14.696 lb-force per $in.^2$ exerted at the base of a column of mercury 29.92 in. high.

Note: In terms of SI (International System) units, this value is 101,325 pascals (Pa), where the pascal is the force of 100,000 dynes acting on a surface area of one square meter. One should note also that on weather maps, pressure is frequently expressed in terms of **millibars**, where a **bar** is a force acting on a surface area of 1 cm^2. Therefore, the standard atmospheric pressure in millibars is 1013.25.

Of course, local atmospheric pressure depends on altitude and weather variations. When an accurate mercury barometer is not available during a source test, one way of obtaining the atmospheric pressure is to call up the local airport weather service. If the number reported to you is a barometric pressure corrected to sea-level, the value must be corrected back to correspond to the altitude at the test location. The correction factor is -0.06 in. for every 50 ft of altitude (height) from the sea level value.

We have just discussed standard atmospheric pressure, but we know that the atmospheric pressure changes. The heating and cooling of the atmosphere contributes to changes in air density and the daily highs and lows of regional and local air pressures. In stacks and ducts, pressures also change. Due to the movement of air through constrictions, or sudden expansions, the gas pressure in a flue can vary (Figure 2-4).

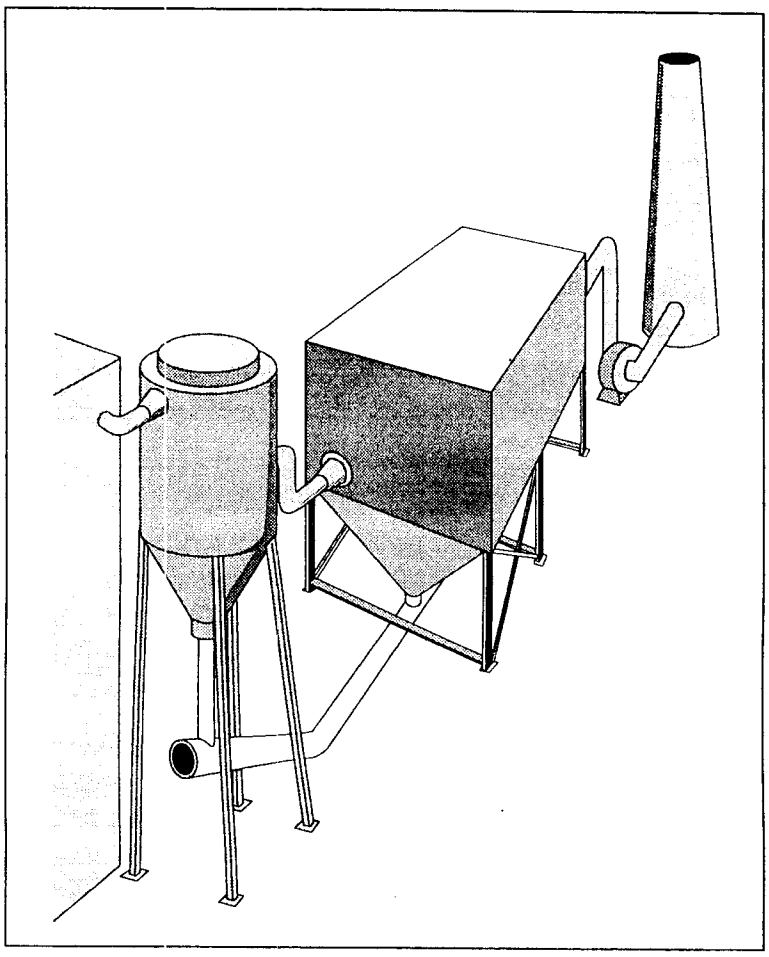

Figure 2-4. Variation of stack static pressure in a duct

Stack testers understand this all too well. If you open a port and stack gas blows into your face (with all of its constituents, such as acid gas and fly ash), you know that the stack pressure is positive. If the rags you use to stop up the port keep getting sucked into the flue, you know that the pressure is negative. This pressure is known as the **stack static pressure** and is given the symbol, p_s. We will discuss the methods used to measure this pressure later, but most of the methods use some type of manometer or gauge that expresses the pressure value in inches of water.

Most source test calculations, however, require that the pressure values used are absolute pressures. The gauge pressure may be either positive or negative with respect to the prevailing atmospheric barometric pressure. Therefore, the actual pressure of the gas molecules acting against our wall or the surface of our balloon can be expressed as:

$$P_s = P_b \pm p_s/13.6 \quad (2\text{-}12)$$

Where: P_s = the absolute stack pressure in in. Hg
P_b = the barometric pressure in in. Hg
p_s = the stack static pressure or gauge pressure in in. H_2O
13.6 = a conversion factor (13.6 in. H_2O = 1 in. Hg)

This discussion of pressure may seem like a digression, but the use of absolute pressures in our calculations is just as important as using absolute temperatures. So let us continue further with our description of the effects of pressure on a volume of gas.

One can perform a simple experiment with our balloon. We could blow the balloon up and seal it in Miami and then fly to Denver or to Death Valley, California to see what happens. We would expect that the balloon would expand in Denver, since at the higher altitude, the atmospheric pressure is less than in Miami, where the balloon was blown up. Alternatively, in Death Valley, which is below sea level, the volume of the balloon would decrease, due to the higher pressure at that location.

With similar experiments and reasoning, Robert Boyle stated in 1660 that "The volume of a fixed mass of gas at constant temperature is inversely proportional to the pressure." Boyle's law can be written as follows:

$$V = (\text{constant})/P \quad (2\text{-}13)$$

Where: P = the absolute pressure

Now, if we know the volume of a given amount of gas at one pressure, the volume can be determined at another pressure by the expression:

$$\frac{P_1}{P_2} = \frac{V_2}{V_1} \quad (2\text{-}14)$$

or,

$$V_2 = \frac{P_1}{P_2} V_1 \quad (2\text{-}15)$$

where the subscript 1 refers to the original conditions and the subscript 2 refers to the new conditions. Variations of Eq. 2-14 are used frequently in source test calculations.

The Ideal Gas Law

Charles' law states that, when the volume is held constant, the absolute pressure of a given mass varies directly as the absolute temperature; whereas Boyle's law states that, when the

temperature is held constant, the volume varies inversely as the absolute pressure. These two concepts can be combined into an expression known as the **ideal gas law.**

$$PV = \frac{m}{M}RT \quad \text{or} \quad PV = nRT \tag{2-16}$$

Where: P = absolute pressure
V = volume of a gas
m = mass of gas
M = molecular weight of a gas
n = number of moles of gas
T = absolute temperature
R = universal gas constant

The unit of R depends upon the units of measurement used in the equation.

Some useful values are:

(1) $R = 1544 \frac{(lb)\ (ft)}{(lb-mole)\ (°R)}$

(2) $R = 21.83 \frac{(in.\ Hg)\ (ft^3)}{(lb-mole)\ (°R)}$

(3) $R = 554.6 \frac{(mmHg)\ (ft^3)}{(lb-mole)\ (°R)}$

(4) $R = 82.06 \frac{(cm^3)\ (atm)}{(gm-mole)\ (°K)}$

In the above units of R:

V = ft^3, cm for (4)
m = lb, g for (4)
M = lb/lb-mole, g/g-mole for (4)
T = °R, °K for (4)
P = lb/ft^2 for (1)
= in. Hg for (2
= mmHg for (3)
= atm for (4)

Any value of R can be obtained by utilizing the fact that, with appropriate conversion factors, there are 22.414 L per gm-mole or 359 ft^3 per lb-mole at 32°F and 29.92 in. Hg.

The ideal gas law applies to perfect, ideal gases. The ideal gas consists of "idealized" molecules that (1) are imagined as points in space (have no volume) but do have mass and velocity, (2) do not attract or repel each other, and (3) do not lose energy when they collide with each other or the walls of a container. The ideal gas law works quite well at the conditions of pressure and temperature encountered in stack testing. Of course, as the gas density increases and real molecules come closer together, the law begins to break down and corrections have to be applied. Such corrections are normally not necessary in stack test calculations.

This expression gives all the necessary information for calculations involving volume, pressure, temperature and the number of molecules of gas. It eliminates the need for dealing with the individual expressions such as Boyle's law and Charles' law. The ideal gas law is expressed in terms of four variables: P, V, T, and n. It can be used in all types of calculations to tell us how one variable will be affected as the others change.

Several useful expressions can be easily derived from Eq. 2-15. One is the temperature/ pressure correction formula routinely used in source sampling:

$$V_2 = \frac{T_2 P_1}{T_1 P_2} V_1 \qquad (2\text{-}17)$$

where again, the subscript 1 refers to the original conditions and the subscript 2 refers to the new conditions.

Another useful relationship relates to gas density. Density is the mass of a substance per unit volume, and for ideal gases, can be expressed as:

$$\rho = \frac{m}{V} \qquad (2\text{-}18)$$

or

$$\rho = \frac{MP}{RT} \qquad (2\text{-}19)$$

Correcting to Standard Conditions

The ideal gas law is typically used to correct from stack conditions of pressure and temperature to a set of standard conditions. We can rewrite Eq. 2-17 as:

$$V_{std} = \frac{T_{std} P_s}{T_s P_{std}} V_s \qquad (2\text{-}20)$$

where the subscript std stands for standard conditions, and the subscript s stands for stack conditions. We will become familiar with the use of this formula in the equations used in the reference methods.

The EPA standard conditions (SC) are:

$$P_{std} = 29.92 \text{ in. Hg } (760 \text{ mmHg})$$
$$T_{std}=528° \text{ R}(293 \text{ °K})$$

(*Note*: The "EPA standard conditions" differ from the "standard temperature and pressure" used in chemistry and physics, which define standard temperature as 0°C (32°F). The EPA standard temperature refers to the typical room temperature condition of 20°C (68°F).)

Gases in Motion

In source testing, much of the work is concerned with flowing gas streams. The source tester must generally calculate the volumetric flow rate of stack gas as well as the flow rate of the gas through the sampling apparatus. Figure 2-5 illustrates a typical flow monitoring situation:

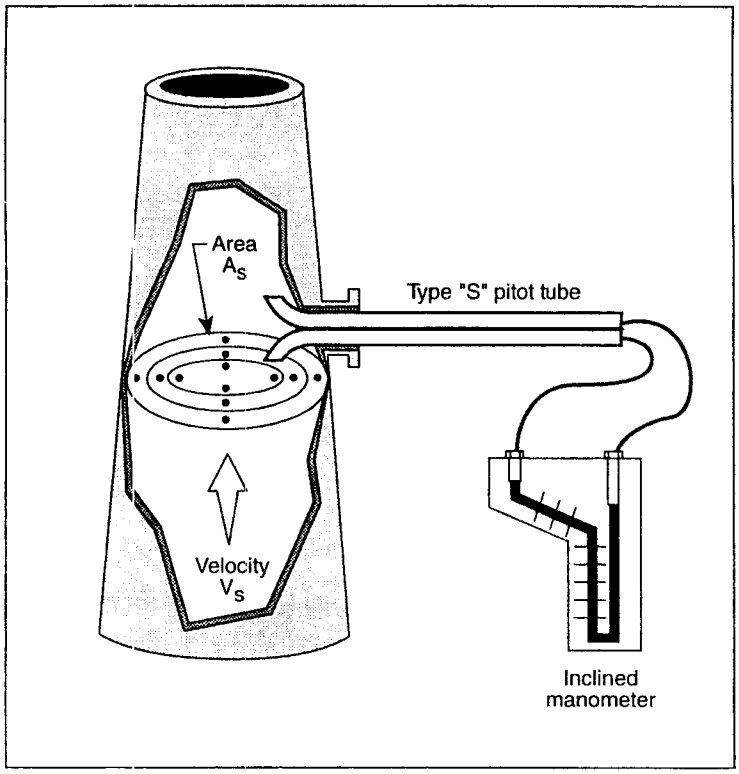

Figure 2-5. Determining the volumetric flow at a stack cross-section

The volumetric flow rate, in units of cubic feet per hour (ft^3/hr) or cubic meters per hour (m^3/hr) can be determined if we measure the flue gas velocity and the cross-sectional area of the stack or duct at the measurement location. The simplest form of the equation is:

$$Q_s = v_s A_s \tag{2-21}$$

Where: Q_s = the stack gas volumetric flow rate in ft^3/hr or m^3/hr
v_s = the flue gas velocity in ft/hr or m/hr
A_s = the cross-sectional area in ft^2 or m^2

If you check this equation dimensionally, you find that:

$$\frac{ft^3}{hr} = \frac{ft}{hr} \times ft^2 = \frac{ft^3}{hr}$$

The volumetric flow rate calculated in this manner would be the flow rate at actual stack conditions. In other words, it gives the flow rate of the stack gas at the stack pressure and temperature. One often uses the abbreviations "acf/hr" or "acfh" to mean actual cubic feet per hour, instead of ft^3/hr in such situations. Most calculations, however, require that this flow rate be corrected to standard conditions. This is done so that data can be comparable between different sources.

Correcting to standard conditions requires the application of the ideal gas law and the correction expression given in Eq. 2-20. Combining Eq. 2-20 and Eq. 2-21, we have:

$$Q_{std} = \frac{T_{std} P_s}{T_s P_{std}} v_s A_s \tag{2-22}$$

The abbreviation "scf/hr," standard cubic feet per hour, is commonly used when the flow rate is corrected to standard conditions.

Going one step further, the volumetric flow rate can be calculated as if all the moisture in the gas were removed. This gives a *dry* volumetric flow rate and requires a measurement of the moisture fraction, B_{ws}, of the flue gas. This added correction then gives the following expression:

$$Q_{std} = (1 - B_{ws}) \frac{T_{std} P_s}{T_s P_{std}} v_s A_s \tag{2-23}$$

The abbreviation "dscf/hr," for dry standard cubic feet per hour, is then used to express the units of this calculation.

If we can determine the concentration of particulate matter (or other pollutant) in the flue gas, we can obtain the rate of emission of the particulate matter into the atmosphere in terms of mass per unit time. This rate is called the **pollutant mass rate**, pmr_s, and can be expressed in units of lb/hr, ton/yr, or kg/hr, depending upon which conversion factors you wish to use.

The pollutant mass rate is obtained from the volumetric flow rate and the concentration by the simple expression:

$$pmr_s = c_s Q_s \qquad (2\text{-}24)$$

Where: pmr_s= the pollutant mass rate in lb/hr, ton/yr, kg/hr
c_s = the pollutant concentration in lb/ft^3, kg/m^3
Q_s = the volumetric flow rate in ft^3/hr, m^3/hr

One can also check this expression dimensionally to see that it makes sense.

Bernoulli's Principle

Daniel Bernoulli was a Swiss scientist who, in the 1800s, studied the relationships between pressure and fluid velocity. His work led to a relationship called **Bernoulli's principle**, which is stated as follows:

The pressure in a fluid decreases with increased velocity of the fluid.

This remarkably simple statement explains many types of physical phenomena: why airplanes fly, why flags flap, why baseballs curve, and so on. In a practical sense for source testing, Bernoulli's principle provides the basis for developing flow rate measuring devices such as the pitot tube and the orifice meter.

When a fluid is moving, energy is contained in the fluid in different forms. Some of that energy is associated with the internal pressure of the fluid and some is associated with the flow of the fluid, or its kinetic energy. If a liquid or gas is flowing through a tube which suddenly becomes constricted, (Figure 2-6), what happens?

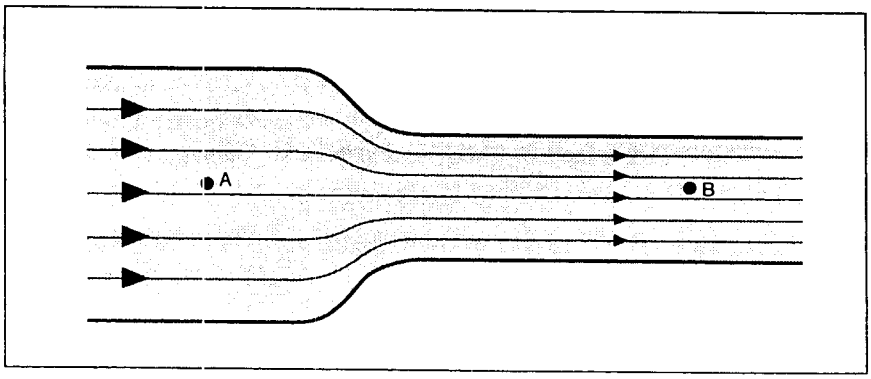

Figure 2-6. Fluid flow through a constricted tube

In Figure 2-6, streamlines are used to represent smooth paths of flow. The closer they are bunched together, the higher the fluid velocity.

If we think of our everyday experience, we realize that the fluid must speed up as it flows through the narrow part of the tube. For example, the flow of water in a brook will increase as

the banks of the brook narrow. This principle can also be demonstrated with a garden hose. As we decrease the nozzle size of a hose, we are able to direct water farther into the garden.

For the water to move faster through the narrows of the brook, it must obtain energy from somewhere. This increase in kinetic energy comes from the internal pressure of the fluid. Note from Figure 2-6 that the pressure at point A must be higher than at B; otherwise the fluid would not be flowing through the constriction. If the pressure is less at point B than at point A, we should be able to measure the difference. Let us modify our tube of Figure 2-6 by installing vertical pressure taps on the tube as shown in Figure 2-7.

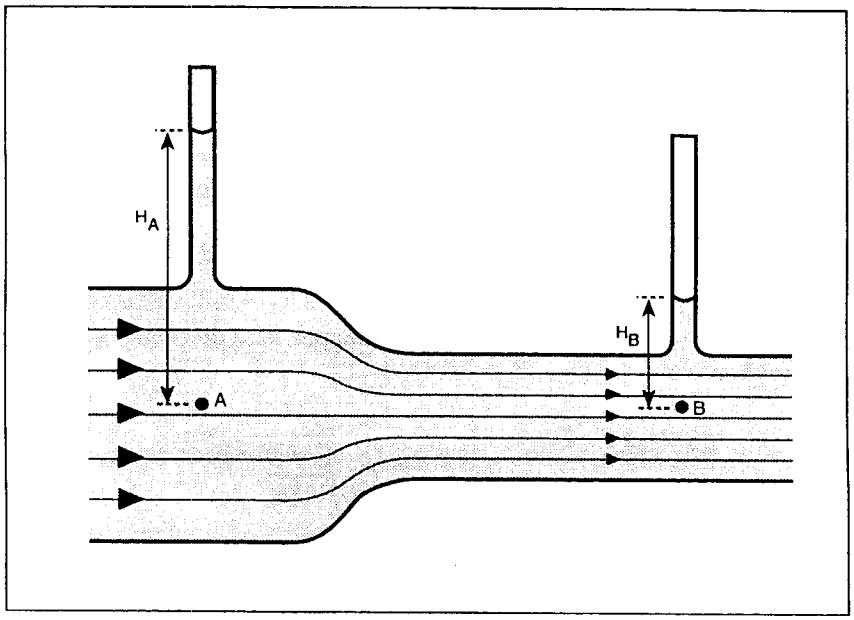

Figure 2-7. Monitoring the pressure on a constricted flow tube. The total energy at point A (the internal, potential energy plus the kinetic energy) is equivalent to the total energy at point B. At point B, the internal energy is less and therefore the pressure is lower.

The pressure has decreased in the constriction as seen from the decreased height of the fluid in the pressure tap. Here, the flow rate of the fluid has increased at the expense of the internal pressure. The molecules are moving forward, rather than bouncing off the walls.

The pitot tube equation for flue gas velocity in Method 2 and the orifice meter equation used in Method 5 are derived from the Bernoulli principle and Bernoulli's equation, which is the mathematical expression of the principle. Both the pitot tube and orifice meter are simple devices that are used to measure gas flow. They are illustrated in Figures 2-8 and 2-9.

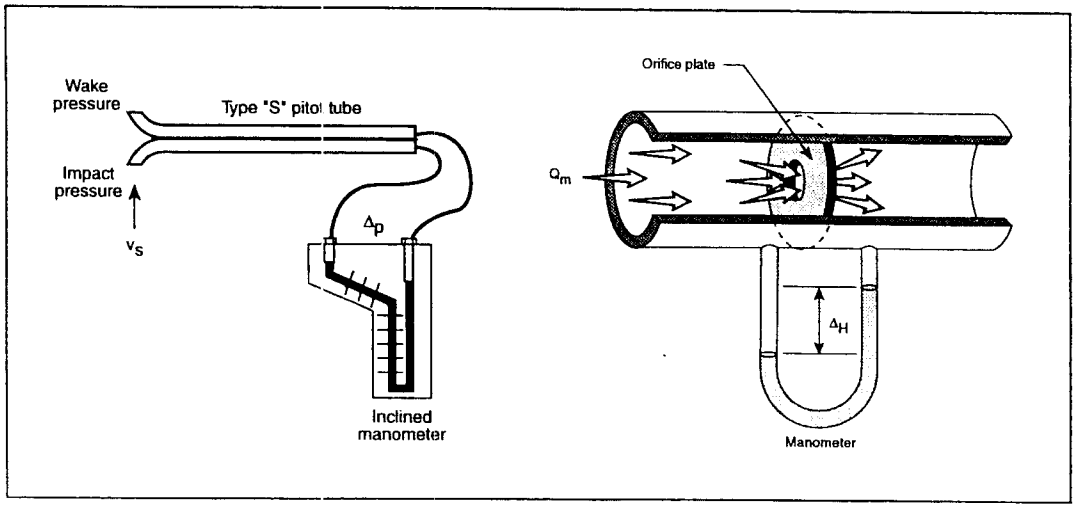

Figure 2-8. The pitot tube

Figure 2-9. The orifice meter

Note that each device has two pressure taps and measures the difference in pressure between the two, the Δp or ΔH, which is sometimes called the **pressure drop** or **pressure differential**. Because of the form of Bernoulli's equation, the pressure drop enters into flow calculations under a square root:

$$v_s = K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}} \qquad (2\text{-}26)$$

$$Q_m = K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}} \qquad (2\text{-}27)$$

Where: v_s = flue gas velocity (m/sec, ft/sec)

K_p = units factor

$$34.97 \frac{m}{sec} \left(\frac{(g/g-mole)\ (mmHg)}{(°K)\ (mmH_2O)} \right)^{1/2}$$

or

$$85.49 \frac{ft}{sec} \left(\frac{(lb/lb-mole)\ (in.\ Hg)}{(°R)\ (in.\ H_2O)} \right)^{1/2}$$

T_s = stack temperature (°K or °R)

Δp = velocity head of the stack gas (pressure drop)(mm H_2O or in. H_2O)

P_s = absolute stack pressure (mmHg, in. Hg)

M_s = stack gas molecular weight (g/g-mole, lb/lb-mole)

(*Note*: The derivation of these equations are given in Appendix A.)

For the orifice meter equation:

Q_m = volumetric flow rate through orifice meter (m^3/sec, ft^3/sec)
K_m = orifice meter calibration factor (determined in lab)
T_m = absolute dry gas meter temperature (°K, °R)
ΔH = pressure differential across orifice (mm H_2O, in. H_2O)
P_m = absolute meter pressure (mmHg, in. Hg)
M_m = molecular weight of gas passing through meter (g/g-mole, lb/lb-mole)

Note that the equations are very similar. You may have seen other expressions of these equations in terms of gas density instead of pressure, temperature, and molecular weight. Conversions can easily be made. However, the preceding equations are used in source testing and the reference methods and will be referred to throughout this manual.

The Pollutant Mass Rate Revisited

This manual has been developed to describe the procedures used to sample for particulate matter in flue gases. The reference method for particulate matter, Method 5, is actually a combination of several different techniques. As we have seen in Eq. 2-24, to obtain the pollutant mass rate, one must obtain two measurements: the particulate mass concentration and the gas volumetric flow rate. The pollutant mass rate equation can be combined with the pitot tube equation to obtain the **wet-basis** expression for the flue gas volumetric flow rate in lb/hr or kg/hr.

$$pmr_s = 3600 c_s A_s K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}} \qquad (2\text{-}28)$$

The pollutant mass rate is the end result that we seek in source testing. We might wish to express our emissions in other units, such as ng/joule or lb/mm Btu, and suitable calculations will be given for doing such conversions. But the goal here is to describe how to obtain these values so that they can be used for either source operations or regulatory purposes.

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Chapter 3

The Method 5 Sampling Train

Description and Theory

We have seen in Chapter 1 that particulate emission standards have been established for many stationary sources. The most common method used to determine whether a source is in compliance with these standards is EPA Reference Method 5, Determination of Particulate Emissions from Stationary Sources, found in the U.S. Code of Federal Regulations and also provided for you as a separate document with this course. The sampling techniques used in Method 5 were developed over a period of time since the 1950s and have been widely used both in North America and in Europe. Method 5 requires both technical knowledge and common sense to be conducted properly, but the procedures are straightforward and give reliable data regarding flue gas particulate emissions.

Isokinetic Sampling

Method 5 requires that a special type of sampling technique called **isokinetic sampling** be performed when sampling for particulate matter. Rather than just inserting a probe into a stack and pulling out a sample at some arbitrary flow rate, isokinetic sampling requires that the sample be drawn into the probe nozzle at the same rate as it is moving in the flue gas (Figure 3-1).

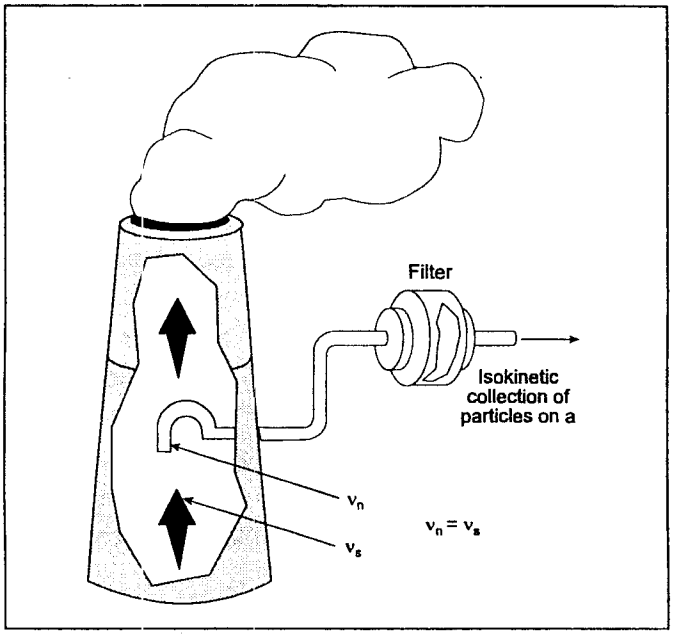

Figure 3-1. Isokinetic sampling

When you break apart the word "isokinetic," you have "iso," which means "the same as," and "kinetic," which pertains to motion. Isokinetic sampling therefore means that you are sampling the gas at the same rate it is moving through a stack or duct. In terms of the variables we use in source test calculations, the isokinetic requirement is:

$$v_n = v_s \qquad (3\text{-}1)$$

In order to collect a representative sample of particulate matter, isokinetic sampling is necessary because of the way particles behave in a gas stream. Particles will normally follow gas streamlines as they move through the plant ductwork or stack. However, if the gas stream makes a sudden turn, or a disturbance modifies the streamlines, the particles may not be able to follow in the same direction as the gas (Figure 3-2).

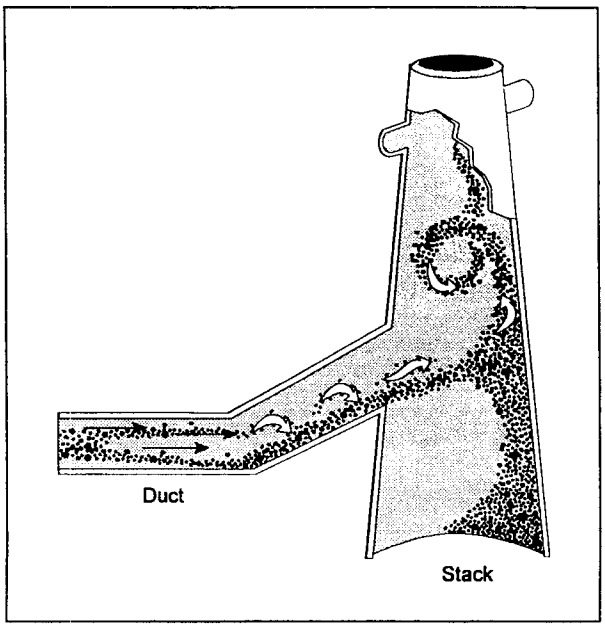

Figure 3-2. Particles in a gas stream

The inertia of large particles will cause them to move in their initial direction, which may in turn result in their colliding with the walls of the duct or otherwise penetrating through the streamlines.

Particle sizes vary in emission sources, as we have seen in Chapter 1, but generally there will be a distribution of sizes in the flue gas stream. In most flue gas situations, one may generalize that large particles are those that are greater than 5 μm in diameter and small particles are those less than 1 μm in diameter. The inertia, or momentum, of a particle will, of course, depend upon its density. Particles between 1 and 5 μm are in a somewhat intermediate range—their behavior in streamlines being more dependent on their density and the gas velocity.

In isokinetic sampling, a sample is taken that does not distort the streamlines. If the sample is isokinetic, the distribution of particles sizes (from small to large) entering the probe will be exactly the same as that in the flue gas itself. In other words, the particulate sample will be representative of the flue gas particle size distribution. This is the ultimate goal of isokinetic sampling—to obtain a representative sample. (Figure 3-3)

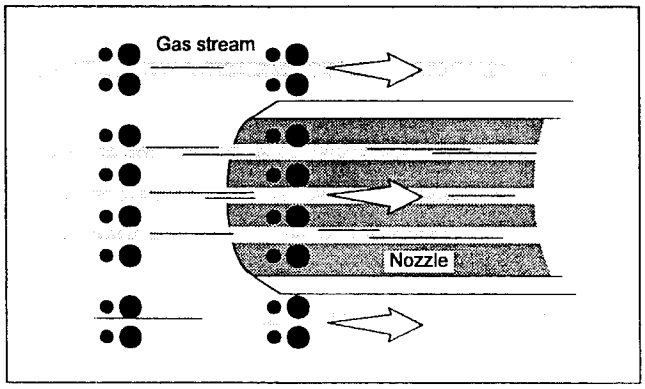

Figure 3-3. Isokinetic sampling conditions

However, if the sample rate, v_n, is too low or too high with respect to the stack gas velocity, v_s, the sampling is said to be **anisokinetic** and errors may result in the particulate concentration measurements. To see the effect of anisokinetic sampling, refer to Figure 3-4.

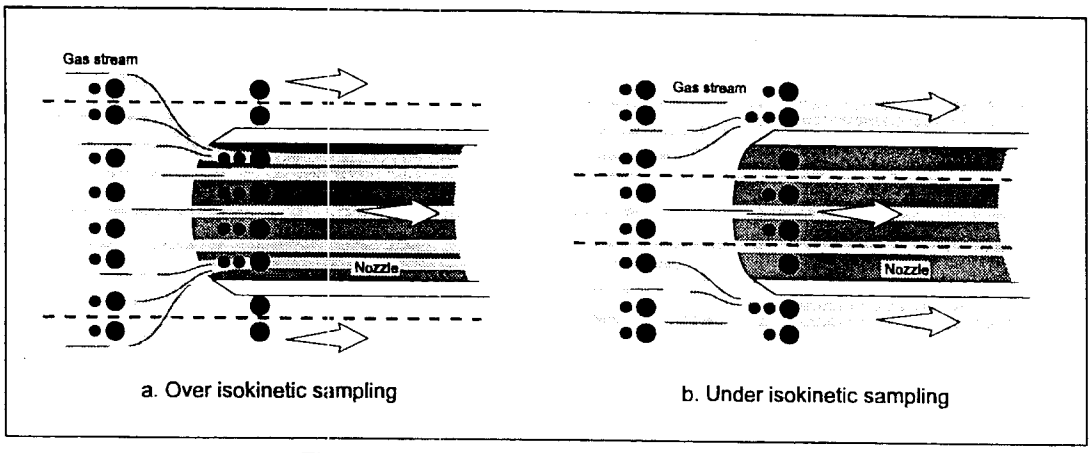

Figure 3-4. Anisokinetic sampling conditions

When the sampling is not isokinetic, problems develop in the region of the curved streamlines near the nozzle inlet. When the nozzle inlet velocity is greater than the stack gas velocity (Figure 3-4a), the nozzle brings in gas from regions not directly in front of it. Gas streamlines converge at the nozzle inlet to brings in a volume of gas greater than one would obtain under isokinetic conditions. Here, the large particles, because of their inertia, do not follow the streamlines, but break through them to continue in the same direction. An analogy here might be the failure of a semi-trailer truck to make a curve, heading off into a farmer's field. When large particles fail to follow gas streamlines, a representative number of large particles will not be included with the greater volume of gas sampled. The particulate distribution in the sample will not be representative and the particle concentration of the sample will be *low*.

When the nozzle inlet velocity is less than the stack gas velocity (Figure 3-4b), the nozzle is bringing the gas in at too low a rate. The gas streamlines bunch up at the nozzle inlet, almost as if it were an obstruction. Here, we are sampling at a rate lower than the flue gas velocity, so we are bringing in a smaller volume of gas than if we were to sample isokinetically. However, the large particles in the gas stream that should slip pass the nozzle instead punch through the streamlines into the nozzle inlet due to their inertia. We now have too many large particles for the smaller volume of gas collected, and our particulate concentration is too high.

In these two situations, small particles followed the streamlines and an appropriate number of small particles would be collected. In fact, if we could be assured that we had only small particles and that they followed streamlines, we wouldn't have to sample isokinetically. However, in most sampling situations, we have a distribution of sizes—from small to intermediate to large—and we must sample isokinetically to obtain a representative distribution of the particles in the sample.

One other problem may arise in sampling. Although we may be sampling isokinetically, the nozzle may be misaligned (Figure 3-5).

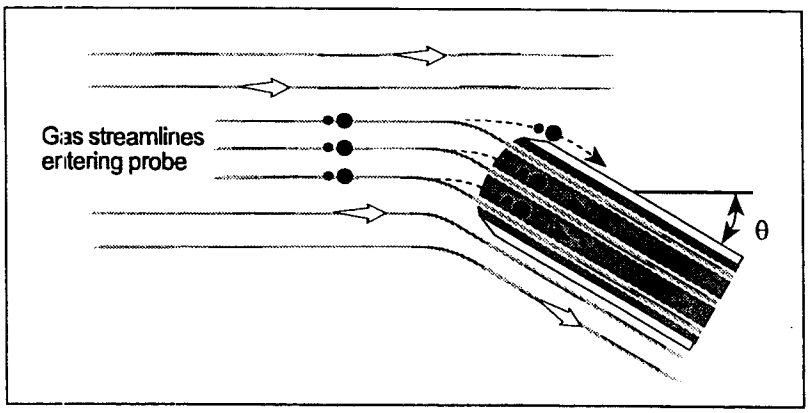

Figure 3-5. Nozzle misalignment

Here, the streamlines bend into the nozzle inlet, but the large particles are not able to make the turn. These large particles will therefore not be included in the sample and the resultant particulate concentration will be too low.

The Method 5 Sampling Train

We now should recognize that it is essential to sample isokinetically if we wish to obtain a representative distribution of particle sizes in our sample. The Method 5 sampling apparatus has been designed to perform isokinetically. The apparatus—often called a **sampling train**—has several components, each having a different function. The Method 5 sampling train is shown in Figure 3-6.

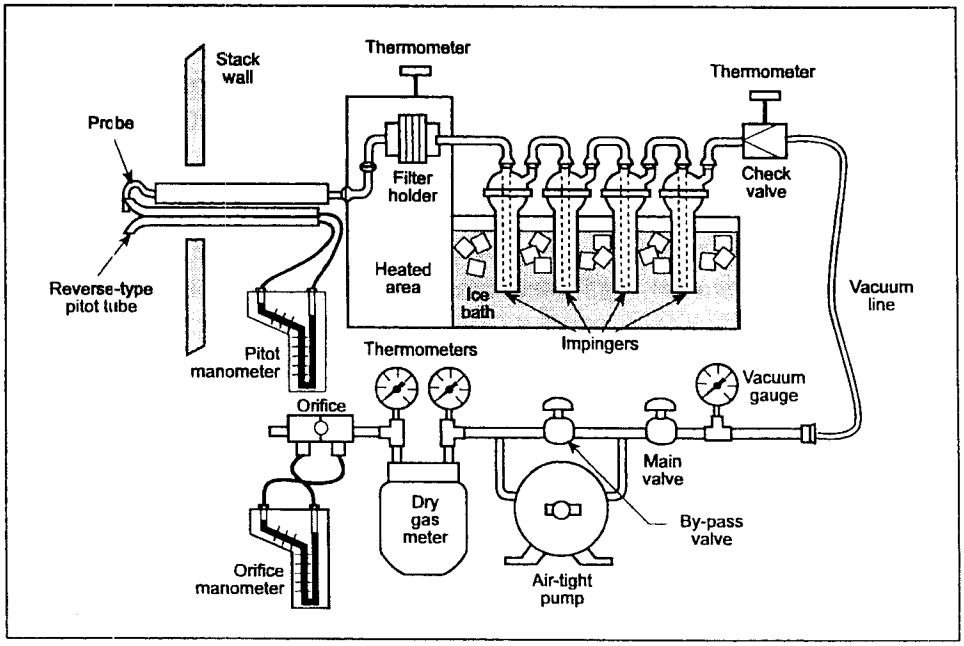

Figure 3-6. Schematic of a Method 5 sampling train

Operation of the Train

The Method 5 sampling train is designed to determine both the stack gas velocity, v_s, and the nozzle inlet gas velocity, v_n. When one knows the value of v_s, then one can adjust the flow of gas through the sampling train so that the gas velocity at the nozzle inlet equals v_n.

When performing a source test, the test team may first conduct a number of preliminary tests in order to obtain information necessary to operate the Method 5 train. These preliminary tests may include the determination of the average flue gas velocity, the flue gas molecular weight, the gas temperature, static pressure, and the moisture content. In frequently tested sources, this information may already be available; in some cases, the values are assumed.

With the preliminary data in hand, the source tester calculates the approximate size of the nozzle that will allow the system to collect approximately 30 dscf of gas over a one-hour period. Once the nozzle is selected, the sampling train is assembled and leak-checked.

Another calculation is then performed by solving the **isokinetic rate equation**. This calculation is necessary in order to know how to adjust the sampling pump and obtain a flow rate through the nozzle that is equivalent to the stack gas velocity. Before the advent of hand-held calculators and portable computers, special slide rules and nomographs were commonly used to perform this calculation. (A **nomogram** is a graphical representation of a formula that requires some manipulation of scales and lines to obtain a result that one might otherwise have to calculate. A **nomograph** is a device that is constructed to assist in this manipulation, much like a slide rule.)

As we shall see, the isokinetic rate calculation is a lengthy one (but not overly complicated). The source tester does not have the time to calculate the values by longhand while testing, and therefore various stratagems were devised to obtain the isokinetic rates. Today, many source testers use calculators or computers, but others still prefer nomographs or slide rules.

When performing the source test, an average value of the emissions must be obtained over the stack or duct cross-section. The gas velocity and/or particulate concentration may be stratified in the flue. For example, Figure 3-7 illustrates velocity isopleths in a rectangular duct.

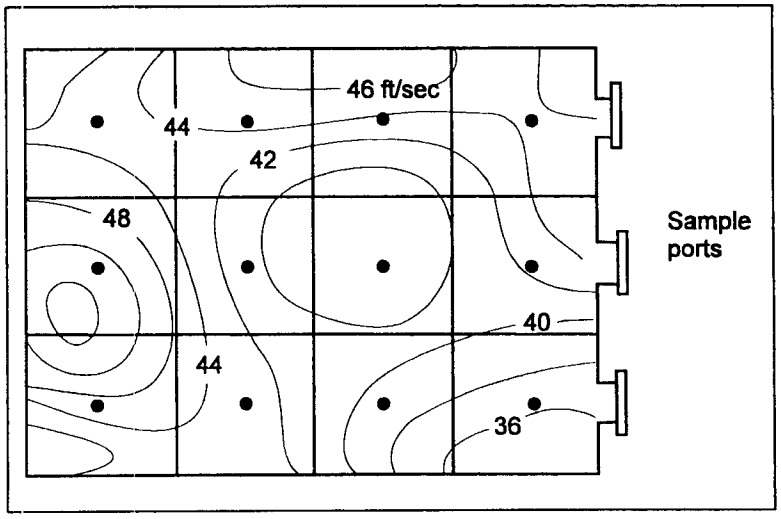

Figure 3-7. Variation of gas velocity in a rectangular duct and Method 1 traverse points

Since the gas velocity and particulate concentration may vary from point to point, EPA requires that sampling be performed over the cross-section, not at just one point. This requires the application of Method 1 criteria which lays out the grid of points at which one is to obtain a sample. In Figure 3-7, an imaginary grid is superimposed on the rectangular duct. When performing Method 5, sampling is conducted at each point of the grid to obtain an area-averaged total sample.

However, since the velocity of the gas is different at each point, the isokinetic sampling rate will be different at each point. This then is what we use the isokinetic rate equation for —to adjust the flow of the gas through the sampling train so that we are sampling isokinetically at each point.

But how do we adjust this flow rate? This is done using the orifice meter and the fine control knob, which is shown just above the pump in Figure 3-6. The orifice meter tells us the flow rate of the gas that exits the Method 5 train, Q_m, where Q_m is a volumetric flow rate in ft^3/sec and determined by using the orifice meter equation (Eq. 2-27) given in Chapter 2. By knowing how fast the gas is exiting the train, we can back-calculate how fast it is coming into the front end of the train. By knowing how the ice bath (Figure 3-6) affects the volume of the sample (by changing its temperature and dropping out the moisture), we can know exactly what the nozzle gas velocity, v_n, is, or alternatively, we can calculate the flow rate of gas through the nozzle, Q_n:

$$Q_n = A_n v_n \tag{3-2}$$

Where: Q_n = nozzle volumetric flow rate (m^3/sec, ft^3/sec)

A_n = cross-sectional internal area of the nozzle (m^2, ft^2)

v_n = velocity of gas in nozzle (m/sec, ft/sec)

By using the isokinetic rate equation, we determine the orifice meter reading, ΔH, that will give us the proper nozzle flow rate. The fine control knob is then adjusted until the ΔH value on the orifice meter manometer is the same as that which we calculated.

The fine control knob adjusts a by-pass valve. From Figure 3-6, we can see that if the by-pass valve were fully open, the pump would just be drawing on itself and we wouldn't be pulling a vacuum through the system. As we close the valve, the vacuum increases and the flow rate of the gas through the nozzle increases. By opening and closing this fine control valve, we can correspondingly decrease or increase the suction at the nozzle, or correspondingly, decrease or increase the flow rate of the gas through the orifice meter.

So, in a one-hour test, with 12 traverse points, the following principal steps are performed when conducting the isokinetic sampling method.

- The sample probe, with pitot tube attached (Figure 3-6), is inserted to a traverse point.
- The Δp reading, indicating the pressure drop across the pitot tube and consequently the flue gas velocity, v_s, is read on the pitot tube oil manometer (or equivalent pressure gauge).
- Using this value of Δp and the isokinetic rate equation, we determine the pressure drop across the orifice meter that will give the proper sampling rate through the nozzle.
- The fine control knob is adjusted until the value of ΔH calculated from the isokinetic rate equation is obtained. The vacuum, or suction, of the Method 5 train is then such that the velocity of the gas in the nozzle, v_n, is equal to the flue gas velocity, v_s.
- Sampling is conducted for five minutes at the point. If the gas velocity should change during the five minutes, the ΔH value is recalculated and the fine control knob readjusted to maintain an isokinetic sampling rate through the nozzle.
- After five minutes, the probe is moved to the next point, the Δp reading is obtained at that point, and a new ΔH value is calculated. The fine control knob is adjusted again to obtain a flow rate through the system that will result in the proper gas velocity through the nozzle.
- This procedure is repeated for all the traverse points so that a sample of approximately 30 dscf is obtained over a one-hour period. This volume is measured by the dry gas meter. Of course, any particulate matter associated with this volume of gas is either caught on the filter or deposited in the probe. The particulate matter is collected and weighed and the concentration of particulate matter in the flue gas is obtained by dividing the mass of the particulate matter collected by the volume of the gas sampled in order to collect it.

The Isokinetic Rate Equation

We are now going to derive the isokinetic rate equation. Since this derivation is central to an understanding of the Method 5 train, please don't skip this part. Please follow along with the derivation. The mathematical techniques are just those of simple algebra and are basically a matter of multiplying and dividing a number of symbols.

The isokinetic rate equation relates the measured value of the pressure drop, Δp, across the pitot tube to the pressure drop, ΔH, across the orifice meter, which we need to know if we are to sample isokinetically. The form of the isokinetic rate equation is simple, and is

$$\Delta H = K\Delta p \tag{3-3}$$

Where: K = an assemblage of constants and parameters that we obtain in our calibration procedures and source test pre-survey or otherwise assume

To obtain an expression for K, we first consider the conditions necessary for isokinetic sampling. If we turn on the sampling pump of the Method 5 train, flue gas will be sucked through the nozzle, the filter, and impingers, and then pushed through the dry gas meter and the orifice meter. The suction on the nozzle draws flue gas into the system at a velocity v_n, or volumetric flow rate of Q_n, as in Eq. 3-1:

$$Q_n = v_n A_n \qquad (ft^3/sec, \quad m^3/sec)$$

To sample isokinetically, somehow we must adjust the suction so that we achieve the isokinetic condition:

$$v_n = v_s \tag{3-4}$$

Assuming that we have achieved the isokinetic condition, what does this do to the rest of the system? To answer that question, we must start making some substitutions in Eq. 3-1. First if the nozzle velocity is the same as the flue gas velocity, we can replace v_s for v_n in Eq. 3-3:

$$Q_n = v_s A_n \qquad (ft^3/sec, \quad m^3/sec) \tag{3-5}$$

The end of the nozzle should be circular, so we can express the area, A_n as:

$$A_n = \pi\left(\frac{D_n}{2}\right)^2 \tag{3-6}$$

Where: D_n = the diameter of the nozzle

Substituting Eq. 3-5 into Eq. 3-4, we have:

$$Q_n = v_s\pi\left(\frac{D_n}{2}\right)^2 \qquad (ft^3/sec, \quad m^3/sec) \tag{3-7}$$

We can make one other substitution at this point. In Chapter 2, we were given an expression for the flue gas velocity (the pitot tube equation, Eq. 2-26). Substituting the pitot tube equation into Eq. 3-6, we have:

$$Q_n = K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}}\pi\left(\frac{D_n}{2}\right)^2 \tag{3-8}$$

Note that we already have one part of the isokinetic rate equation, Eq. 3-2. The Δp is under the square root sign of Eq. 3-7.

We can obtain the expression for K in Eq. 3-2 if we can relate the nozzle volumetric flow rate, Q_n, to the orifice meter volumetric flow rate, Q_m. We mentioned earlier that as we pull in sample gas from the duct or stack, we cool it down and drop out the moisture in the impingers in the ice bath. From our discussion of the ideal gas law in Chapter 2, we know that a given volume of gas entering the nozzle is reduced in volume in the impingers, resulting in a smaller volume of gas exiting the train. Let us quantify this effect.

Here, we start backwards, working from the orifice meter to the nozzle. If we know the volumetric flow rate of the gas at the orifice meter (taking into account changes in the temperature and pressure of the gas, and the loss of water molecules), what will be the volumetric flow rate of gas at the nozzle? Or:

$$Q_n = (\text{corrections for T, P, moisture}) \times Q_m$$

If the temperature and pressure of the gas changes from the orifice meter to the nozzle in the sampling train, we must first make an ideal gas law correction to Q_m. To obtain the nozzle volumetric flow rate from the meter volumetric flow rate, we first correct from meter conditions, m, to stack conditions, s:

$$Q_n = \frac{P_m T_s}{P_s T_m} Q_m \tag{3-9}$$

But, if we have moisture in the stack gas, we removed the water molecules in the impingers before they could reach the orifice meter. Therefore, more moles of gas entered the nozzle than left the orifice meter. To obtain the nozzle gas flow rate, we must account for the water vapor entering the nozzle. If B_{ws} is the fraction of water in the flue gas, then we divide Eq. 2-28 by $(1 - B_{ws})$ to correct for the loss of the water in the impingers, or:

$$Q_n = \frac{1}{(1 - B_{ws})} \frac{P_m T_s}{P_s T_m} Q_m \qquad (3\text{-}10)$$

In Chapter 2, we were given the orifice meter equation (Eq. 2-27):

$$Q_m = K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}} \qquad (ft^3/sec,\ m^3/sec)$$

Substituting this equation into Eq. 3-9, we have:

$$Q_n = \frac{1}{(1 - B_{ws})} \frac{P_m T_s}{P_s T_m} K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}} \qquad (3\text{-}11)$$

We now have an expression for the volumetric flow rate of the gas, moving through the nozzle, that we can calculate from measured parameters. This is the last part of our puzzle and we can substitute this expression into Eq. 3-7. Doing this, we obtain:

$$\frac{1}{(1 - B_{ws})} \frac{P_m T_s}{P_s T_m} K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}} = K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}} \pi \left(\frac{D_n}{2}\right)^2 \qquad (3\text{-}12)$$

Notice now that we have an expression that contains both Δp and ΔH—exactly what we were looking for when we started with Eq. 3-2. If we do a little algebra, we can reorder Eq. 3-11 to the form of Eq. 3-2:

$$\Delta H = \{D_n^4 \left(\frac{\pi K_p C_p}{4 K_m}\right)^2 (1 - B_{ws})^2 \frac{M_m T_m P_s}{M_s T_s P_m}\} \Delta p \qquad (3\text{-}13)$$

or

$$\Delta H = K \Delta p \qquad (in.\ H_2O,\ mm\ H_2O)$$

This is the isokinetic rate equation which allows the source tester to adjust for isokinetic flow through the nozzle. In practice, the source tester observes the value of Δp at the sam-

ple point, solves Eq. 3-12, and then sets the fine control knob on the Method 5 train meter box until the calculated value of ΔH is reached on the orifice meter manometer. This process is repeated at each traverse point or even during sampling at one traverse point if the flue gas velocity is varying at that point. A source tester will typically calculate the K factor before the test run. If all of the parameters remain relatively constant during the test, then it becomes necessary to multiply K by the new Δp reading at each traverse point.

There is another form of Eq. 3-12, the working form, that is more commonly used. The working form of the equation substitutes a different expression for the orifice meter calibration factor, K_m. We can rearrange the orifice meter equation, Eq. 2-27, by solving for ΔH:

$$\Delta H = \frac{Q_m P_m}{K_m^2} M_m \qquad (3\text{-}14)$$

Instead of using K_m as the orifice meter calibration factor, the expression $\Delta H_@$ is used in source testing in the United States. The expression $\Delta H_@$ is defined as the orifice meter pressure differential that gives a flow rate of 0.75 cfm of airflow through the meter at 68°F and 29.92 in. Hg If we substitute these conditions into Eq. 3-13, we have:

$$\Delta H_@ = \frac{(0.75\text{cfm})^2 (29.92\text{in.Hg})}{(460 + 68°\text{F})\, K_m^2} 29.0\ (\text{lb/lb} - \text{mole}) \qquad (3\text{-}15)$$

or

$$\Delta H_@ = \frac{0.9244}{K_m^2}$$

The value of K_m is determined when the orifice meter is calibrated. This is usually done in the laboratory before going into the field. The expression, $\Delta H_@$ is useful since it denotes that, in a 60-minute period, approximately 45 ft^3 of gas will be sampled by the train at an orifice meter pressure differential of $\Delta H_@$.

Then, taking Eq. 3-14 and the fact that $K_p = 85.49$, we can substitute these into Eq. 3-12 to obtain the working form of the isokinetic rate equation.

$$\Delta H = \{846.72 D_n^4 \Delta H_@ C_p^2 (1 - B_{ws})^2 \frac{M_d T_m P_s}{M_s T_s P_m}\} \Delta p \qquad (3\text{-}16)$$

One can also derive a corollary expression from Eq. 3-15 to assist in selecting a nozzle. Particulate testing is normally conducted at a flow rate of about 0.75 cfm. If the nozzle diameter is too small, a flow rate much higher than 0.75 cfm may be necessary in order to

sample a minimum of 30 ft^3 of gas in a one-hour period. The pump may not have enough suction power to do this. Also, if the nozzle diameter is too large, at a flow rate of 0.75 cfm, a very large volume of gas might be sampled and the filter could plug up before the one-hour test is completed. So, to choose the nozzle, one first performs a preliminary velocity traverse to obtain an average Δp value, Δp_{avg}. This value is then used in the following expression:

$$D_n = \sqrt{\frac{0.0358 Q_m P_m}{T_m C_p} \frac{1}{(1 - B_{ws})} \sqrt{\frac{T_s M_s}{P_s \Delta p_{avg}}}} \qquad (3\text{-}17)$$

Where: Q_m can be taken at 0.75 cfm or any other desired flow rate.

Having calculated this value, the source tester then finds a nozzle that has a diameter closest to the calculated diameter. For example, if D_n were calculated to be 0.26 in., a quarter inch nozzle (D_n = 0.25 in.) would most likely be selected.

As you can see, these equations are somewhat complicated to solve. They require the entry of a number of constants and measured parameters, and sometimes assumed parameters. Nomographs and special slide rules were originally developed to solve these equations. When the techniques of using these devices are learned, they become very convenient in the field and the calculations can be performed very quickly. However, handheld calculators and portable computers are supplanting these devices. Calculations can be performed even more quickly with such calculators, but one must be particularly careful of keying errors when they are used. Also, particulate matter and acid gases in the test environment can foul calculators and computers. But if care is taken to protect a computer in such an atmosphere, a great deal of flexibility can be programmed to cross-check results and present source test data.

Specialized Equipment

Specialized equipment is required for performing the experimental procedures outlined in Method 5. This equipment may be either constructed by the source tester or purchased from a commercial vendor. It is more common today to find stack test consulting companies and agency test teams using commercial equipment.

Figure 3-8 illustrates an actual Method 5 sampling train.

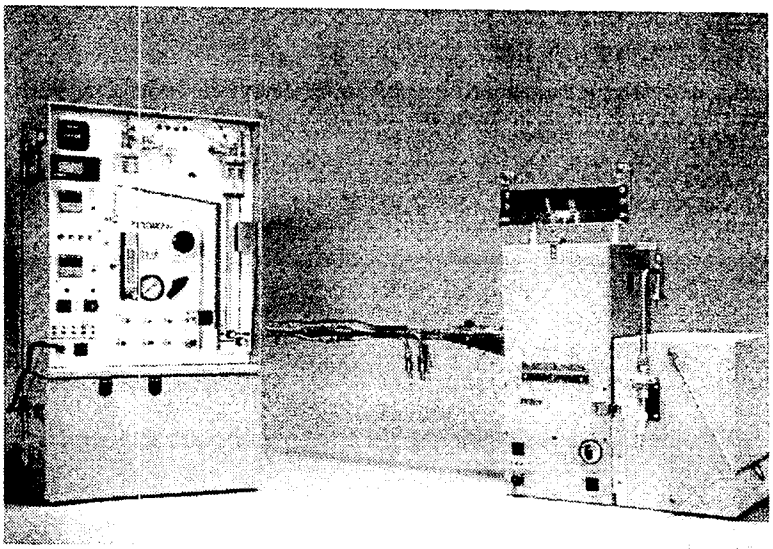

Figure 3-8. Photograph of a Method 5 sampling train

There are, of course, many commercial variations of the train design; however, any train that is constructed or purchased must meet certain requirements. These requirements are given in detail in 40 CFR 60 Appendix A. Highlights of some of these requirements are covered in the following discussion, in which we start with the sample nozzle and go through the separate components of the train.

The Nozzle

Sampling nozzles are commonly constructed of stainless steel or quartz glass. The nozzle must have a sharp outside edge (taper angle ≤ 30°) and a buttonhook or elbow design. This profile creates the least amount of disturbance to the gas streamlines. Figure 3-9 illustrates the preferred sampling nozzle shape.

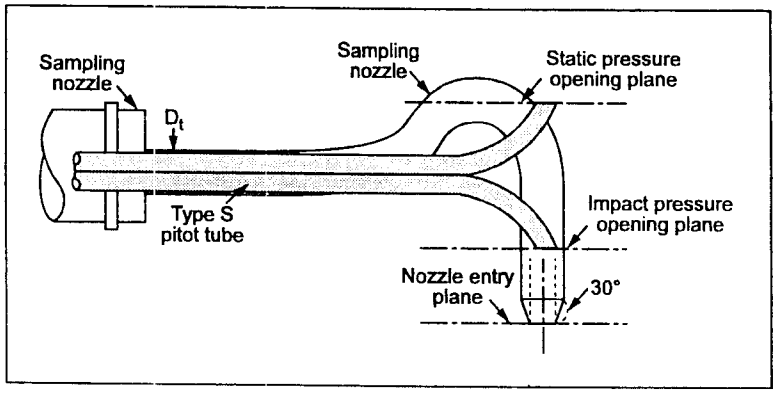

Figure 3-9. Preferred nozzle shape (assembled with a Type S pitot tube)

The nozzle interior diameter must be accurately measured using calipers. The manufacturer's nozzle calibration is only a nominal approximation, and calibration of nozzle interior diameter should be checked before it is placed on the sampling probe at the test site.

The sampling nozzle interior diameter must be round and uniform throughout its entire length. If the tip is out-of-round it must be rounded, ground to a sharp edge, and recalibrated. If the nozzle has obvious flat places in its body, it should be replaced with a nozzle of uniform diameter.

The nozzle must be properly aligned with the pitot tube so that a line can be drawn through the central axis of the interior nozzle diameter opening and the pitot opening. The nozzle must not be too short or too long. If the central axis of the pitot tube is not on the same line as the nozzle diameter, it must be parallel and not more than 1/4" off-center (Figure 3-10).

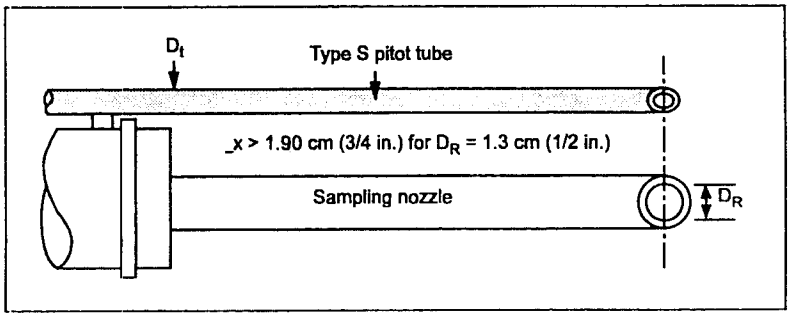

Figure 3-10. Nozzle alignment with the pitot tube

The Pitot Tube

The Stausscheibe (Type S) pitot tube is the pitot tube most frequently used in conjunction with Method 5. The Type S pitot tube has several advantages that make it attractive for source sampling applications:

- It is compact. It is easy to insert into a 3 in. sampling port.
- It retains calibration in abusive environments.
- It has large sensing openings that minimize the chance of plugging in heavy particulate concentrations.
- It indicates a higher Δp reading than a standard pitot tube—a feature that is beneficial in measuring low gas velocities.

The Type S pitot tube is not a designated standard. It should be calibrated against a standard pitot tube having a known calibration factor. In this calibration, one obtains the C_p value that we have seen in Eq. 2-26. If the tube is constructed according to the detailed design specifications of the Method (40 CFR 60 Appendix A), one may use an assumed value of $C_p = 0.84$ instead of performing a calibration.

Sample Probe - Pitot Tube Assembly

The pitot tube should be firmly attached to the sampling probe and arranged in such a way that the pitot tube body will be oriented perpendicular to the stack wall when sampling. The sensing openings will then be perpendicular to the flow of gas parallel to the stack. This orientation is necessary for precise, accurate gas velocity readings. The pitot must be firmly attached to the probe so it will not slip accidentally into misalignment.

The sample probe consists of a probe sheath and a probe liner and incorporates a heater to bring it up to stack temperature (Figure 3-11). The nozzle, of course, is attached to the end of the probe and connects to the probe liner. The pitot tube is attached to the probe.

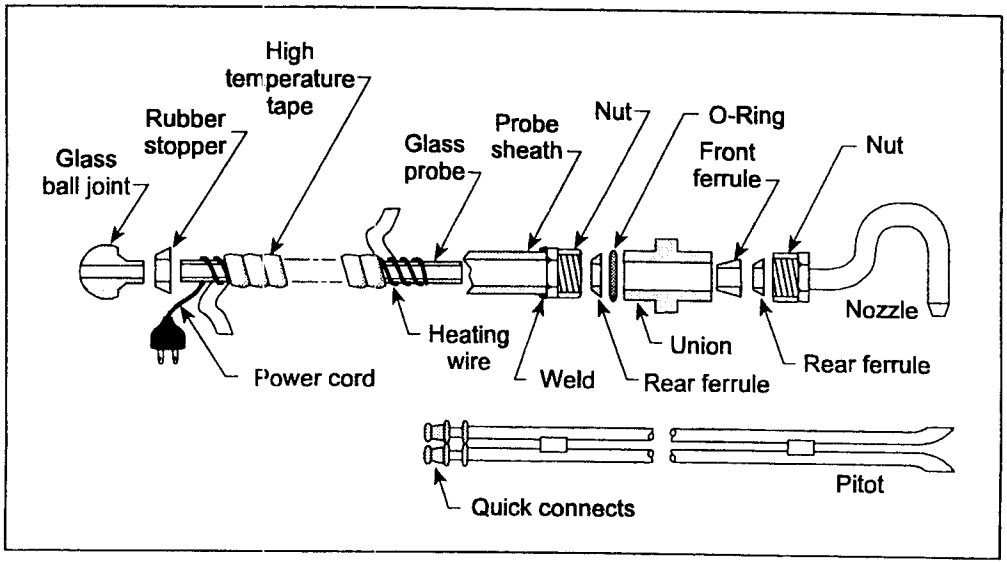

Figure 3-11. The sample probe - pitot tube assembly

The stainless steel probe sheath should be of 316 stainless steel or equivalent. The sheath should be at least 3 in. from the pitot tube openings, and the nozzle must be at least 0.75 in. from the pitot tube when attached to the probe (Figure 3-10). A small hole should be drilled into the stainless steel sheath to equalize any pressure differential that might allow dilution air to be pulled into the sampling system.

The sheath is designed to protect the heated liner. The system should be designed so that the probe liner heating element does not short circuit. The liner should be borosilicate glass for sampling stack gases below 700°F. Quartz glass may be used in the sheath for temperatures up to 1400°F. Stainless steel liners are subject to corrosion by hot, acidic stack gases. They should be a last choice except for very difficult sampling applications or for sampling probes over 11 ft. long. A liner heated by an easily removed, reusable heating element can be replaced at minimum cost. The probe heater should be calibrated so that the outlet gas temperature at the filter is known.

The Sample Case

A lightweight, easily adaptable sampling case is an asset during sampling experiments. The case should be solidly constructed and have well-insulated electrical connections. The filter compartment must have a calibrated thermostat. A positive locking system to prevent probe-pitot rotational or tilt misalignment in the stack is also necessary. Also, the design should be such that the probe sheath can be inserted into the sample case so that there is no accidental glass breakage.

There are several types of impinger-filter sets available for source sampling trains. Sample case impingers and filter holders are generally made of Pyrex glass. Glass has obvious advantages and should be used unless unusual situations arise, which may call for stainless

steel or Lexan plastic equipment. An example of typical sample case glassware is illustrated in Figure 3-12.

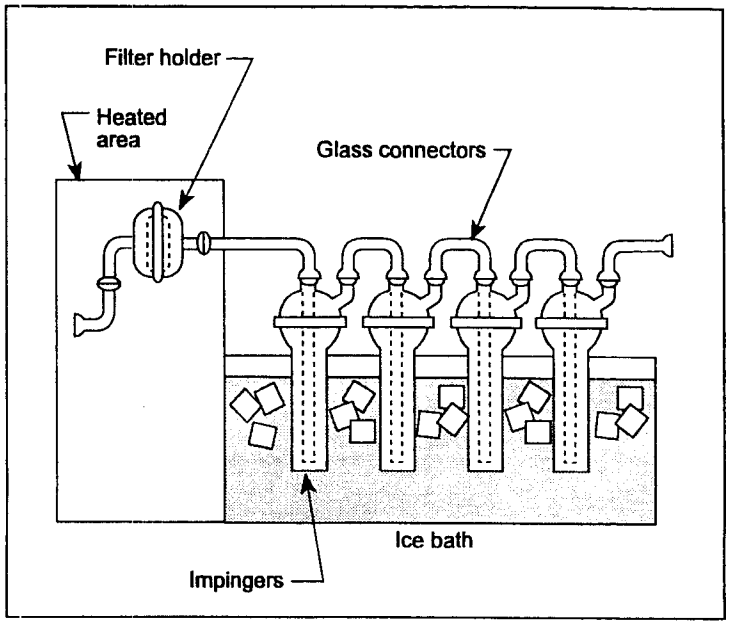

Figure 3-12. Method 5 glassware

Glassware is available in standard ball joint fittings that are sealed with vacuum grease and clamped together, or in a screw-joint sealed with a compressible Teflon rubber ring. The screw-joint fittings may increase breakage; however, they are easier to clean, and grease contamination of the sample is minimized.

The Umbilical Cord

The vacuum sampling line, pitot tube lines, and electrical wiring are wrapped into an **umbilical cord** extending from the meter console to the sample case (Figure 3-13).

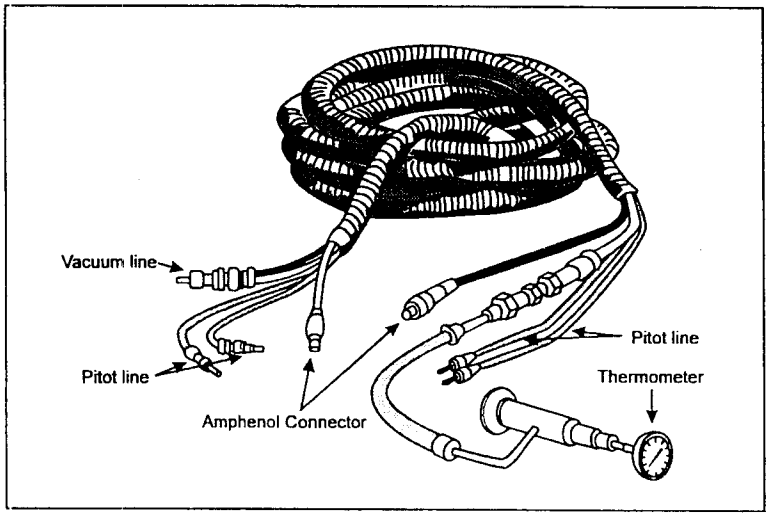

Figure 3-13. The umbilical cord

These lines are encased in tape or shrink tubing to protect them and eliminate clutter at the sample site. The vacuum line should be of high-vacuum rubber tubing. The pitot lines are best constructed of heavy-ply Tygon tubing. These materials make the umbilical cord heavier, but they are not easily melted, burned, or cut. Sample cords made of polymeric materials can be easily damaged and begin to leak. The electrical wires should have thick insulation to prevent fraying in heavy use. They should be color-coded and attached to an Amphenol connection for easy hookup to the sample case.

The Meter Box

The meter box is the center of the sampling system. The meter box consists of a packaged system that includes the pump, dry gas meter, orifice meter, manometers, and system valving and controls. In some designs, the pump or meter box is provided in separate or attachable boxes in order to reduce the weight and provide greater ease in handling (Figure 3-14).

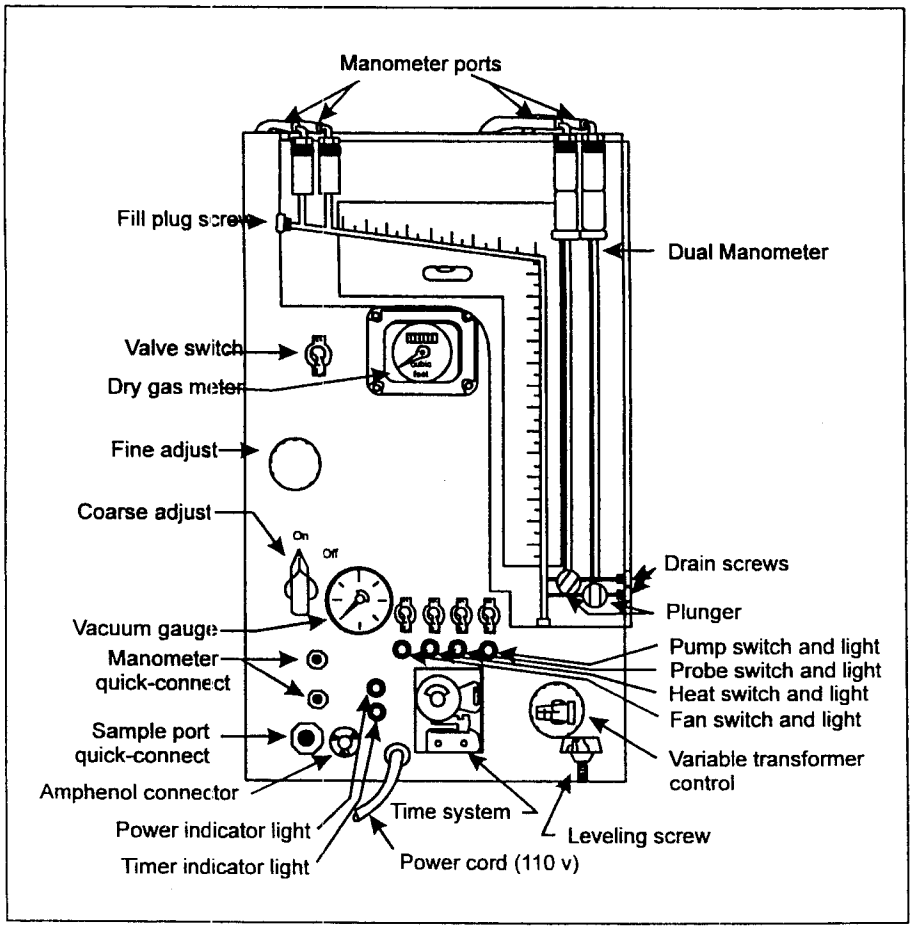

Figure 3-14. A typical meter box

The system must have a leak-free pump to draw an isokinetic sample. A fiber vane, oil-lubricated pump, or diaphragm pump capable of creating an absolute pressure of ≤ 3 in. Hg is recommended. A fiber vane pump is more desirable than a diaphragm pump,

because it does not give "pulses" of gas that can create errors in the operation of the dry gas meter.

The pump should force gas into the dry gas meter inlet; rather than pull it through the meter outlet. The dry gas meter sliding vane seals are adversely affected when under vacuum, so a vacuum gauge should be in the system to measure the pressure drop across the sampling train.

The dry gas meter must be accurate. The manufacturer supplies a nominal calibration curve with the meter that should be rechecked before using the meter. A dry gas meter correction factor developed by calibration against a spirometer or wet test meter is important for volume readings from the meter. The meter dial face should measure 0.1 ft^3 of gas per revolution, which gives the most precise volume reading.

The differential pressure gauge recommended in Method 5 is an oil manometer. The manometer must be capable of measuring the velocity pressure to within 1.3 mm (0.05 in.) water column. The oil manometer is a secondary standard and is very accurate. A Magnehelic gauge may be used if it is calibrated before a test series, then checked after each test series against an oil manometer. The Magnehelic gauge must be calibrated and checked at three Δp readings representing the range encountered at the source. The Magnehelic gauge and oil manometer must agree within 5% for the Magnehelic gauge to be considered in proper calibration. Electronic manometers (pressure transducers) are also frequently used in test situations.

The meter console or equivalent apparatus must be capable of monitoring and maintaining all the equipment temperatures in addition to measuring stack gas temperature. Bimetallic thermometers in the sample case for impinger gas exit temperature are acceptable if they are precise to within 1°C (2°F). The temperature at the dry gas meter and at the filter compartment must be measured with a precision of 3°C (5.4°F).

Some method of regulating the calibrated probe liner heater and filter heater must be incorporated into the temperature control system. The stack gas temperature meter must measure gas temperature to 1.5% of the minimum absolute stack gas temperature. A meter console using thermocouples for these operations must have the thermocouples calibrated regularly and checked before each use.

Alternative Methods and Equipment

There are a number of alternative methods that can be used for the isokinetic sampling of stack gas particulate matter. European methods and the International Standards Organization Method (ISO 9096) have received attention in many countries. However, they are all very similar to Method 5, in that they are isokinetic sampling methods.

Differences arise principally in the placement of the filter, an issue that we will discuss later. Other differences occur in the details, such as nozzle design, pitot tube characteristics, limiting temperatures, and so forth. It is not certain how variation in these details will affect the net result of sampling the particulate concentration. However, as long as a set of procedures is standardized, data obtained by those procedures should be comparable to other data obtained using the same procedures.

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Chapter 4

The First Four Reference Methods

The first four source test reference methods are applied before conducting Method 5. If prior knowledge is available or reasonably good assumptions can be made, not all of the methods need to be conducted. But if you look at the isokinetic rate equation (Eq. 3-15) and the nozzle diameter equation (Eq. 3-16), you can see that there are a number of parameters that we must know before we can proceed with isokinetic sampling. The first four reference methods give us the following information:

- Method 1 - Number of traverse points
- Method 2 - Average gas velocity pressure (Δp_{avg}), pitot tube calibration coefficient (C_p), and absolute stack pressure (P_s)
- Method 3 - Wet stack gas molecular weight (M_s)
- Method 4 - Percent moisture of stack gas (B_{ws})

These reference methods are used to provide the preliminary information for setting up Method 5. Used alone, they can provide source emission data for the parameters listed above, as well as other information on flue gas characteristics. The methods are also important in the application of continuous emission monitoring (CEM) systems to stationary sources. The methods are routinely cited in the CEM performance specification criteria of 40 CFR 60 Appendix B, 40 CFR 75 Appendix A, and 40 CFR 266 Appendix IX.

Method 1: Sample and Velocity Traverses for Stationary Sources

Method 1 specifies both the sampling site location and the location of the sampling points to which the source tester will be moving the Method 5 probe during a test. The basic principle behind the method is as follows:

> The more convoluted the ductwork, the more points will need to be tested.

This principle rests on the assumption that if you are testing at a point that is close to a bend in the ductwork, close to a fan, or close to some other disturbance such as the stack exit, the flow will not be uniform. The assumption is that the flue gas velocity and/or the particulate matter concentration could be more stratified the closer we get to a flow disturbance. (For example, see Figure 3-6 in Chapter 3.)

Sampling Site Criteria

According to EPA criteria, a sampling location must be at a point in the stack or ductwork that is eight duct diameters downstream from a disturbance and two duct diameters upstream from a flow disturbance (Figure 4-1).

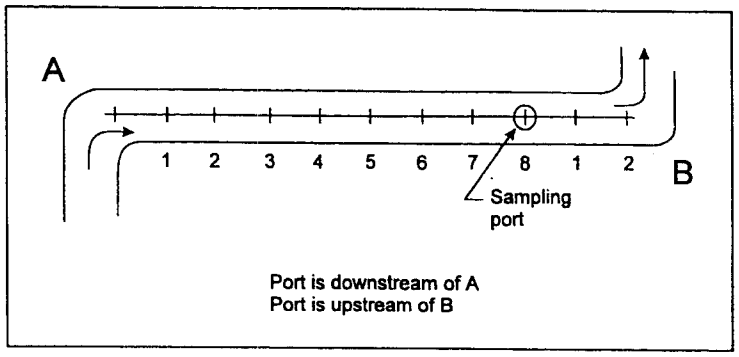

Figure 4-1. A sampling site eight duct diameters downstream and two duct diameters upstream from ductwork disturbances (bends)

Note from Figure 4-1 that the sampling port is relatively far from the first bend in the ductwork. It is commonly assumed that this straight run of ductwork will help smooth out any velocity or particulate stratification that may have been developed by the bend. This may or may not be the case. The eight- and two-duct diameter criterion is arbitrary and does not guarantee that the flow or particulate concentration is uniform at such a point. In fact, in Method 1, an alternate site may be selected if it is only two diameters downstream and one-half diameter upstream from a flow disturbance.

In the case of rectangular ducts, an **equivalent diameter**, D_e is used in the siting and traverse point considerations. For a rectangular duct, this is given in Equation 4-1.

$$D_e = \frac{2LW}{(L + W)} \qquad (4\text{-}1)$$

Where: L = length of the duct
W = width of the duct

This equation is derived from considerations of the "hydraulic radius", which is the cross-sectional area of the duct at the sampling site, divided by the length of the perimeter. If the duct is non-rectangular (e.g., trapezoidal), the derivation technique given in Appendix A of this manual can be used to determine the hydraulic radius and then the equivalent diameter.

If a site does not even satisfy the two-duct and one-half-duct diameter criteria, a special test can be conducted to determine if the site is suitable for sampling. This test, which uses a directional flow-sensing probe (Figure 4-2), can also be used when swirling or cyclonic flow exists in a location that meets the eight-duct and two-duct diameter criterion.

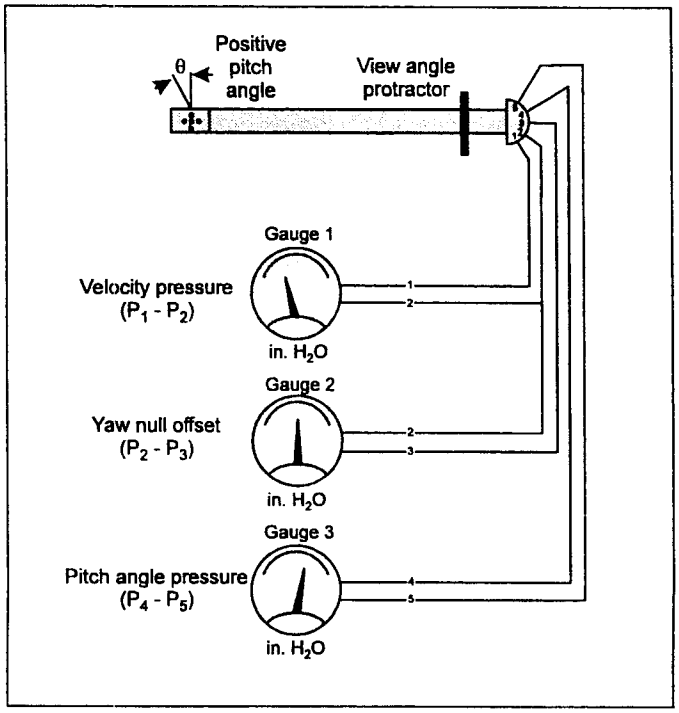

Figure 4-2. A directional flow-sensing probe.

In this test, the direction of the gas flow is determined at 40 or more sampling points on the cross-section. The location is deemed acceptable if the average resultant flow angle is less than 20°. (For an overview and application of the method, refer to Jernigan, 1993.)

Sampling Point Criteria

Once the sampling site is selected, the number of **sampling points** are determined. In Method 1, EPA has established two sets of sampling point criteria: one for velocity traverses, the other for particulate traverses. If a Method 5 test is being conducted, the source tester determines the number of points that must be tested by using a graph in Method 1, 40 CFR 60 (reproduced here as Figure 4-3).

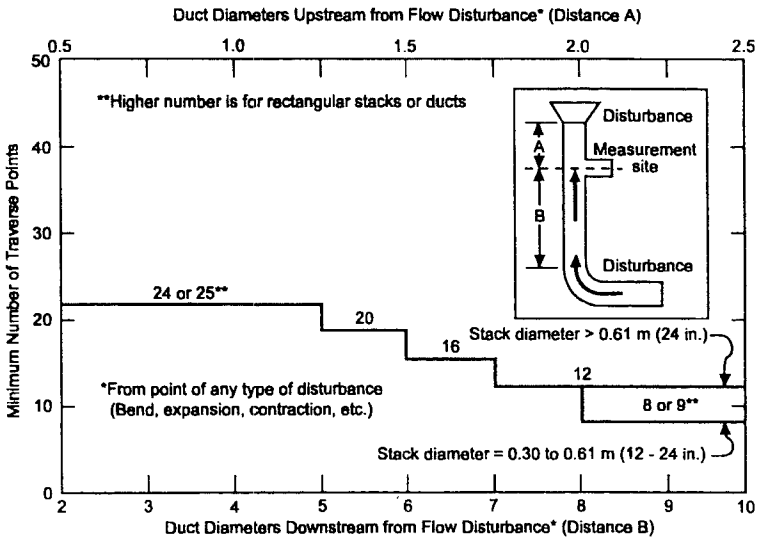

Figure 4-3. Minimum number of traverse points for a Method 5 particulate traverse

To use the graph, mark on the bottom the number of duct diameters the sampling site is *downstream* from a disturbance. Then, on the top of the graph, mark the number of duct diameters the sampling site is *upstream* from a disturbance. From each point, draw a vertical line up or down through the graph to intersect the stepped line. The number of sampling points is given by the number on the step where the vertical lines intersect. If the vertical lines intersect different steps, use the higher numbered step.

Fewer test points are required when performing a velocity traverse. One chooses the velocity traverse points in a similar manner, but instead refers to the traverse point diagram for velocity determinations in Method 1, 40 CFR 60 (reproduced here as Figure 4-4).

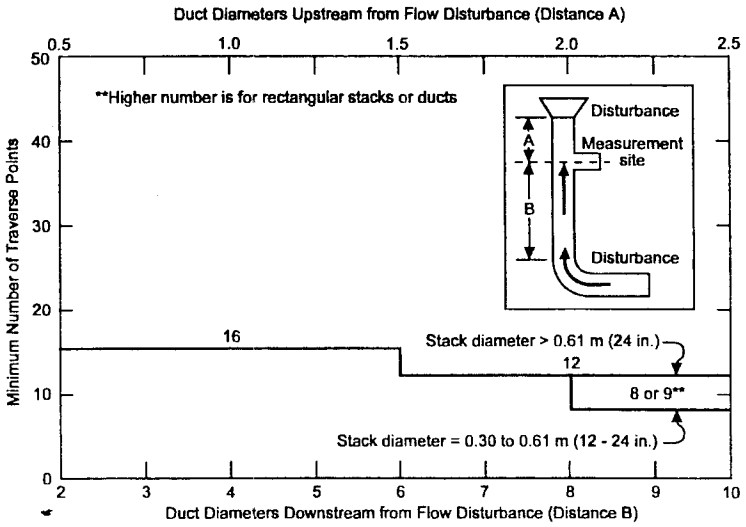

Figure 4-4. Minimum number of traverse points for a velocity traverse

The method for determining the number of traverse points is somewhat arbitrary. The idea is to measure a number of points over the cross-section so that a good, average value can be obtained for the particulate concentration or the flue gas velocity. One might think that the more points that are tested, the better the average would be. In fact, some European standards routinely require testing at 48 points, even at eight- and two-duct diameter locations. It has been found, however, that sampling a large number of points may not necessarily give you a better number (Knapp, 1976). Since flow conditions can change in the duct while you are sampling, the longer you sample, the higher the probability will be that the flow or particulate distribution will change. The numbers given in Figures 4-3 and 4-4 represent a compromise developed by EPA that can result in a cross-sectional average obtainable over a reasonable length of time.

Cross-sectional Layout and Location of Traverse Points

After the number of sampling points has been selected, one must determine where to put them. There are two procedures given in Method 1 for this purpose: one for rectangular ducts, the other for circular ducts.

In a rectangular duct, the requirement is simply that the cross-section be divided into a matrix of equal areas, equal to the number of traverse points (Figure 4-5).

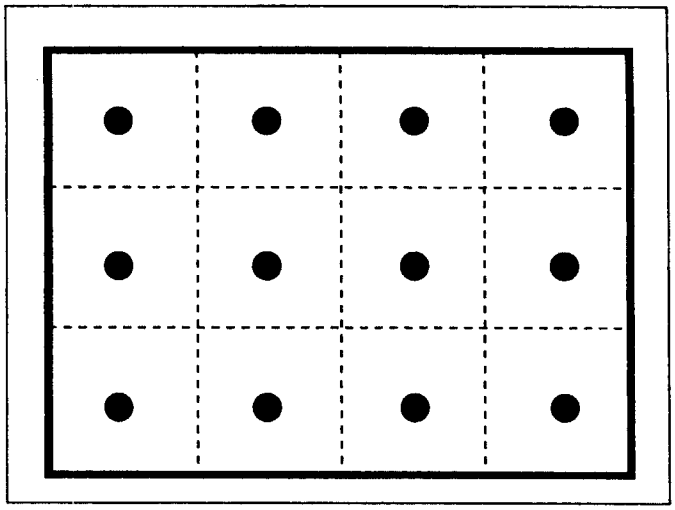

Figure 4-5. Example showing a rectangular duct cross-section for 12 traverse points divided into a matrix of 12 equal areas

The matrix is required to be balanced. For example, one would not be allowed to just put in two ports on the duct of Figure 4-5 and sample at six points across the length of the duct for each port. Method 1 specifies the matrix layout: for 9 points, the layout is 3 x 3; for 12 points, 3 x 4 (Figure 4-5); for 20 points, 4 x 5; and so on. Sampling is then conducted in the center or **centroid** of each of the areas. (If an area were put on the tip of a pin, it would balance at the centroid.)

The determination of traverse point locations for circular ducts or stacks is somewhat more complicated, since the equal areas are semicircular (Figure 4-6).

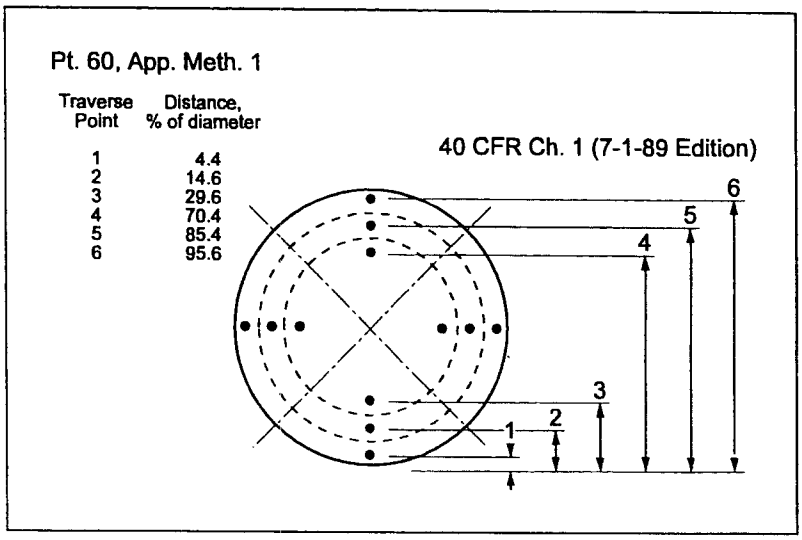

Figure 4-6. Equal areas and traverse points on a circular cross-section

In practice, only two ports are needed for testing on a circular stack. If the probe or pitot tube is long enough, can be supported and does not sag, it can be extended across the stack diameter to test at each point.

The dashed lines of Figure 4-6 divide the cross-section into four equal quadrants, each of which is further divided into equal areas. Traverse points are then located at the centroid of each of these areas. The determination of these points is somewhat complicated. (The equation and derivation for this procedure is given in Appendix A of this manual). However, Table 4-1 allows you to look up these values easily.

Table 4-1. Location of Traverse Points in Circular Stacks
(Percent of stack diameter from inside wall to traverse point)

Traverse point on a diameter	Number of traverse points on a diameter											
	2	4	6	8	10	12	14	16	18	20	22	24
1	14.6	6.7	4.4	3.2	2.6	2.1	1.8	1.6	1.4	1.3	1.1	1.1
2	85.4	25.0	14.6	10.5	8.2	6.7	5.7	4.9	4.4	3.9	3.5	3.2
3		75.0	29.6	19.4	14.6	11.8	9.9	8.5	7.5	6.7	6.0	5.5
4		93.3	70.4	32.3	22.6	17.7	14.6	12.5	10.9	9.7	8.7	7.9
5			85.4	67.7	34.2	25.0	20.1	16.9	14.6	12.9	11.6	10.5
6			95.6	80.6	65.8	35.6	26.9	22.0	18.8	16.5	14.6	13.2
7				89.5	77.4	64.4	36.6	28.3	23.6	20.4	18.0	16.1
8				96.8	85.4	75.0	63.4	37.5	29.6	25.0	21.8	19.4
9					91.8	82.3	73.1	62.5	38.2	30.6	26.2	23.0
10					97.4	88.2	79.9	71.7	61.8	38.8	31.5	27.2
11						93.3	85.4	78.0	70.4	61.2	39.3	32.3
12						97.9	90.1	83.1	76.4	69.4	60.7	39.8
13							94.3	87.5	81.2	75.0	68.5	60.2
14							98.2	91.5	85.4	79.6	73.8	67.7
15								95.1	89.1	83.5	78.2	72.8
16								98.4	92.5	87.1	82.0	77.0
17									95.6	90.3	85.4	80.6
18									98.6	93.3	88.4	83.9
19										96.1	91.3	86.8
20										98.7	94.0	89.5
21											96.5	92.1
22											98.9	94.5
23												96.8
24												98.9

Each number in the table is a percentage of the stack inside diameter. To use Table 4-1, divide the total number of traverse points (determined by using Figure 4-3 or 4-4), by 2(n) and find the n number on the top of the table. Then multiply the diameter at the sampling port by each number to find the distance you must insert the probe into the stack to be at the given traverse point. (However, be careful to adjust this number for the port length.) For example, for a 10 foot diameter stack, with 16 traverse points on the cross-section, go to the column numbered 8 and multiply each number in the column by 10. Then the first traverse point will be 0.32 ft from the stack wall; the second point will be 1.5 ft from the wall; the third, 0.194 ft; and so on. Notice that the center of the stack is not tested.

During a test, the probe or pitot tube is inserted into one port. After each traverse point is tested, the probe is moved to the other diameter. Points on the diameter perpendicular to the first are then sampled to complete the test. For particulate traverses, EPA requires that one diameter be in the plane where you would expect the greatest variation in particulate concentration. For example, after a bend, one diameter should be in the plane formed by the bend.

Method 1 incorporates more details than have been given here. In particular, Method 1A gives criteria for sample traverses for stacks or ducts with diameters less than 1 ft. Since the sampling apparatus itself may interfere in the measurement of such small ducts, special precautions must be taken.

Method 2: Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube)

Method 2 is used to determine flue gas velocity and volumetric flow rate using the Type S pitot tube. Method 2 is also used to certify flow monitors applied in continuous emission monitoring systems. This advanced application can be found in 40 CFR 60 Appendix B and in 40 CFR 75 Appendix A.

The method, as published in the Code of Federal Regulations, is quite lengthy, but most of the details describe how to calibrate the probe. Effectively, if the Type S probe meets certain design criteria, one can assume a value for its calibration coefficient, C_p. Alternatively, one can calibrate the pitot tube in a wind tunnel against a standard (Type L) pitot tube.

The Type S Pitot Tube

In an open tube placed in the direction of flow of the flue gas, gas molecules will give up their kinetic energy of motion at the end of the tube to perform work on the gas already in the tube. This work is sensed as a pressure by the gas already in the tube and can be measured on a manometer as shown in Figure 4-7a.

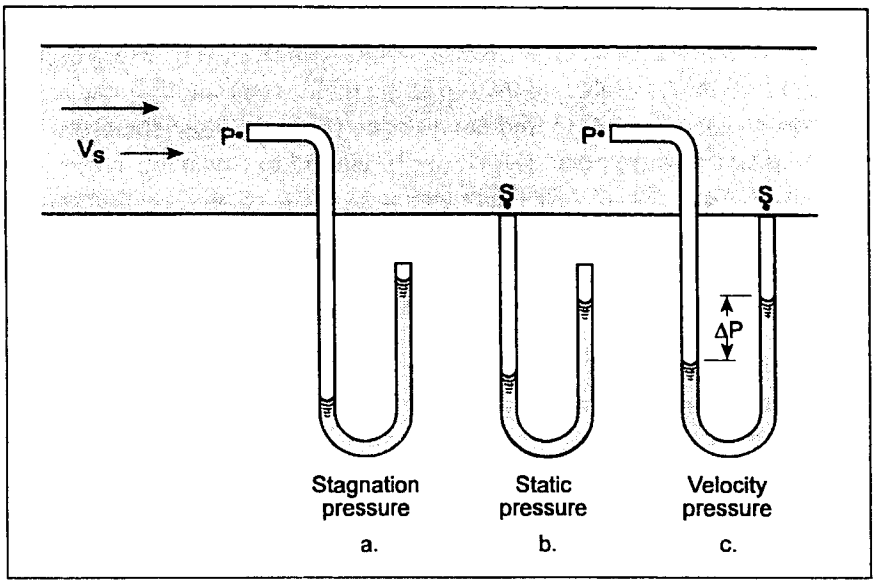

Figure 4-7. Components of pressure in a flowing gas stream

This pressure is known as the **stagnation pressure**.

However, in the duct itself, there is another pressure; the internal or **static pressure**. As discussed earlier, we can sense this somewhat intuitively. If we opened up a port on the stack and flue gas (with acid gas and particulate matter) blew out in our face, we would know that the internal stack pressure is positive. If instead, a glove or a piece of paper were sucked into the stack, we would know that the static pressure was negative. One of the best ways of measuring this pressure is to put a pressure tap on the side of the duct and connect it to a manometer as shown in Figure 4-7b.

The difference between these two pressures, the stagnation pressure and the static pressure, is the **velocity pressure**. The velocity pressure is what the pitot tube measures. In Figure 4-7c, the velocity pressure can be measured by combining the measurement methods for the stagnation and static pressures. The difference in pressure between the two taps as measured on the manometer is known as the **pressure drop**, Δp.

In effect, the velocity pressure measurement is made by subtracting the internal stack pressure contribution (static pressure) from the total pressure at the tip of the tube. This velocity pressure can then be used in the pitot tube equation (Eq. 2-26) to calculate the flue gas velocity.

$$v_s = K_p C_p \sqrt{\frac{T_s \ \Delta p}{P_s \ M_s}}$$

Where: v_s = flue gas velocity (m/sec, ft/sec)
K_p = units factor
C_p = calibration factor

$$34.97\frac{m}{sec}\left(\frac{(g/g-mole)\ (mmHg)}{(°K)\ (mmH_2O)}\right)^{1/2}$$

or

$$85.49\frac{ft}{sec}\left(\frac{(lb/lb-mole)\ (in.\ Hg)}{(°R)\ (in.\ H_2O)}\right)^{1/2}$$

T_s = stack temperature (°K or °R)
Δp = velocity head of the stack gas (pressure drop)(mm H_2O or in. H_2O)
P_s = absolute stack pressure (mmHg, in. Hg)
M_s = stack gas molecular weight (g/g-mole, lb/lb-mole)

(*Note*: The derivation of this equation is given in Appendix A.)

The measurement system shown in Figure 4-7c could be used to measure the flue gas velocity; however, more practical devices have been developed for stack testing. There are many types of pitot tubes that have been designed to measure flow. They all work, in one way or the other, by the Bernoulli principle.

Two devices, the standard pitot or Type L pitot tube (Figure 4-8), and the Type S pitot tube (Figure 4-9) are addressed in Method 2.

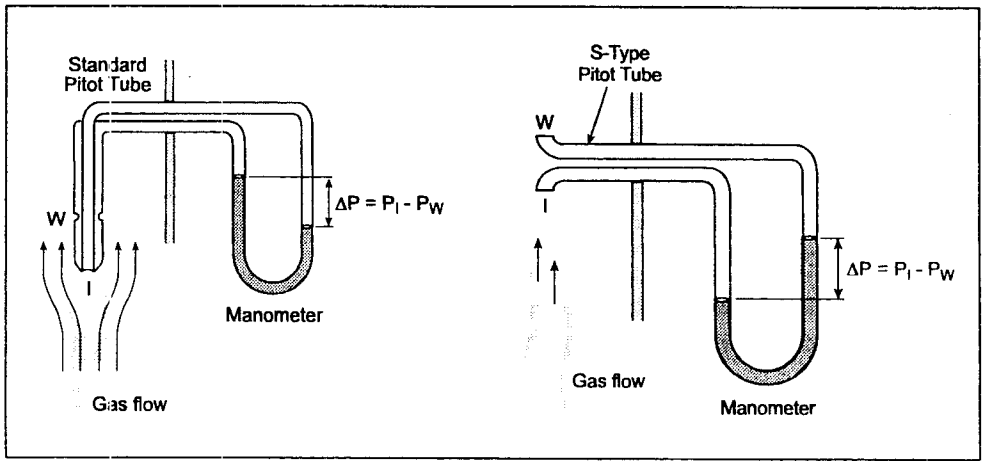

Figure 4-8. The standard (Type L) pitot tube

Figure 4-9. The Type S pitot tube

Each of these tubes measures an impact or stagnation pressure at point I, analogous to the pressure measurement shown in Figure 4-7a and a wake pressure analogous to the pressure of measurement shown in Figure 4-7b. Both the Type L and Type S pitot tubes combine the measurements to obtain the velocity pressure of Figure 4-7c. However, at point W, a **wake pressure** or **pseudo-static pressure** is measured. In the case of the standard or (Type L) pitot tube (Figure 4-8), the wake pressure is very close to the static pressure measured in Figure 4-7b. In the case of the Type S pitot tube (Figure 4-9), however, the turbu-

lence due to the shape of the tube causes the wake pressure to be lower than the true static pressure of the stack.

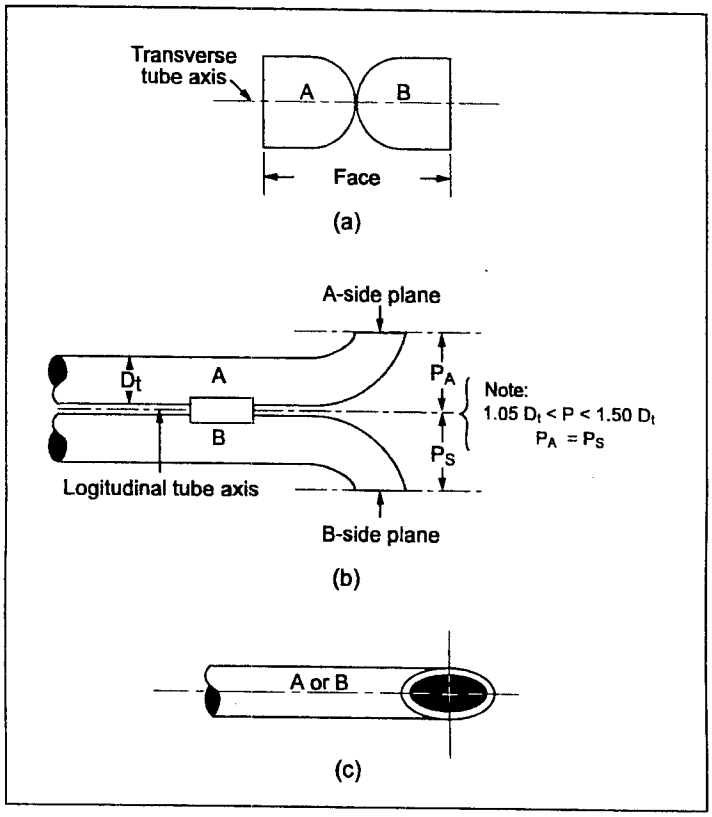

Figure 4-10. Tip of the Type S pitot tube

The differences of the wake pressure from the static pressure can be accounted for through the calibration factor, C_p, in the pitot tube equation. In the standard pitot tube, the C_p will usually have a value from 0.98 to 1.00. In the Type S pitot tube, due to its odd shape and the placement of the wake pressure tube behind the impact tube, the value of C_p will vary from 0.79 to 0.87. In practice, if the Type S pitot tube is designed correctly (see Chapter 7), the value of 0.84 can be assumed. It can, however, be calibrated in a wind tunnel, using the Type L pitot tube as a standard.

The standard pitot tube is usually not used in source testing since the orifices on the side of the tube used to measure the static pressure can become easily clogged with particulate matter. The Type S tube has larger openings. Usually constructed from 3/8 in. tubing, the tubes are less prone to clogging and can be easily blown out if they should become plugged.

Another feature of the Type S tube is that it gives a greater deflection on the manometer than a standard tube. Since the wake pressure is lower than the true static pressure, the Δp will be greater than for the standard tube. This enables the Type S pitot tube manometer to be more readable and the system to measure more accurately than the standard tube at lower flue gas velocities.

Calculating the Average Velocity

When measuring the flue gas velocity with a pitot tube, the tube is inserted into the stack or duct to a Method 1 traverse point. A reading is taken and the tube is moved to the next point. After all the readings have been obtained, an average value for the flue gas velocity can be calculated by averaging the square roots of the Δp readings (Eq. 4-2).

$$(\sqrt{\Delta p})_{avg} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\Delta p_i} \qquad (4\text{-}2)$$

Where: n = the number of traverse points.

Eq. 4-2 then becomes:

$$\overline{v_s} = K_p C_p (\sqrt{\Delta p})_{avg}\sqrt{\frac{T_s}{P_s M_s}} \qquad (4\text{-}3)$$

It is not correct to first average the Δp's and then take the square root. This will give a different answer than the procedure given above.

However, note that several other parameters are needed before one can calculate the velocity. The temperature, T_s, is usually measured using a thermocouple attached to the end of the pitot tube or the Method 5 probe. The molecular weight of the stack gas, M_s is measured by Method 3, a discussion of which follows. Lastly, the stack static pressure, P_s, is calculated by obtaining the local barometric pressure and measuring the stack static pressure (Eq. 4-4).

$$P_s = P_{bar} + \frac{p_s}{13.6} \qquad (4\text{-}4)$$

Where:
- P_s = the absolute stack static pressure in in. Hg
- P_{bar} = the barometric pressure at the test site
- p_s = the stack static pressure measured by a pressure gauge or manometer (in. H_2O)
- 13.6 = unit conversion factor (13.6 in. H_2O = 1 in. Hg)

The static pressure can be measured in several ways. Several methods are shown in Figure 4-11.

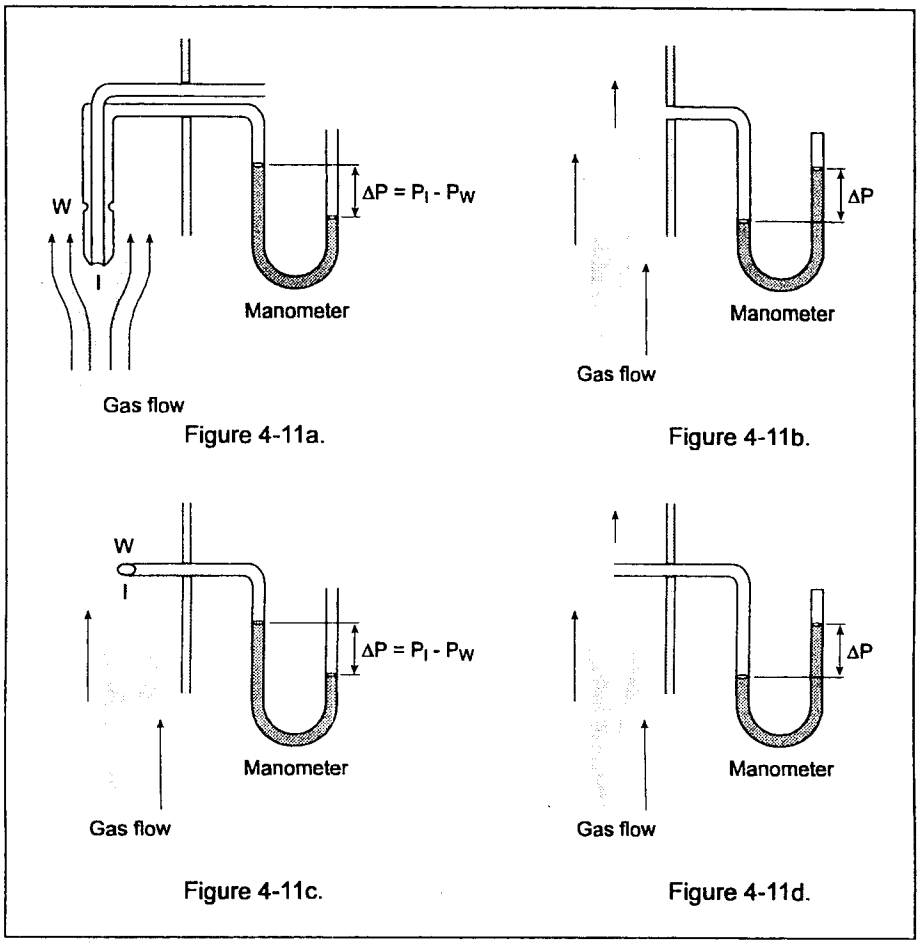

Figure 4-11. Measurement of the stack static pressure

The first method, shown in Figure 4-11a, is conducted by inserting a standard tube in the duct or stack, removing the tubing from the impact pressure side of the manometer, and measuring the pressure of the static tap. This method is quick, convenient, and relatively accurate.

A duct static tap shown in Figure 4-11b will give the best measurement of Δp_s if the tap is flush with the inside wall of the duct and there are no leaks at the tap.

If problems occur with the standard tube due to plugging, or one is not available, the Type S pitot tube (Figure 4-11c) can be used by rotating it 90° from the direction of flow. Detach one of the tubes from the manometer and measure Δp_s. A straight tube (Figure 4-11d) can also be used by inserting it directly into the stack and measuring the pressure. However, these last two methods are not as accurate as the first two, since they both disturb the flow, creating turbulence around the tube opening that can affect the pressure reading. The effect can be pronounced at static pressures less than 1 in. H_2O.

One should note, however, that the accurate measurement of p_s is not critical. Since the *absolute* stack static pressure is used in the pitot tube equation, ± 1 in. $H_2O/13.6$ added to a barometric pressure of 29.92 in. Hg is not particularly significant.

Method 3: Gas Analysis for the Determination of Dry Molecular Weight

The determination of the flue gas molecular weight is necessary for the solution of both the pitot tube equation and the isokinetic rate equation. For combustion processes, the *dry* molecular weight is given by the following expression:

$$M_d = 0.440\,(\%CO_2) + 0.320\,(\%O_2) + 0.280\,(\%N_2 + \%CO) \qquad (4\text{-}4)$$

Method 3 is used in the determination of the $\%CO_2$, $\%O_2$, and %CO, if carbon monoxide is present at percentage levels. The nitrogen percentage is obtained by difference from 100. For emission sources that contain percentage levels of other gases, the composition of the flue gas must be determined and Eq. 4-4 modified to reflect that composition. The general equation is:

$$M_{mix} = \sum B_i M_i \qquad (4\text{-}5)$$

Where: B_i = mole fraction of gas i
M_i = molecular weight of gas i

Method 3 specifies the use of an Orsat analyzer (Figure 4-12).

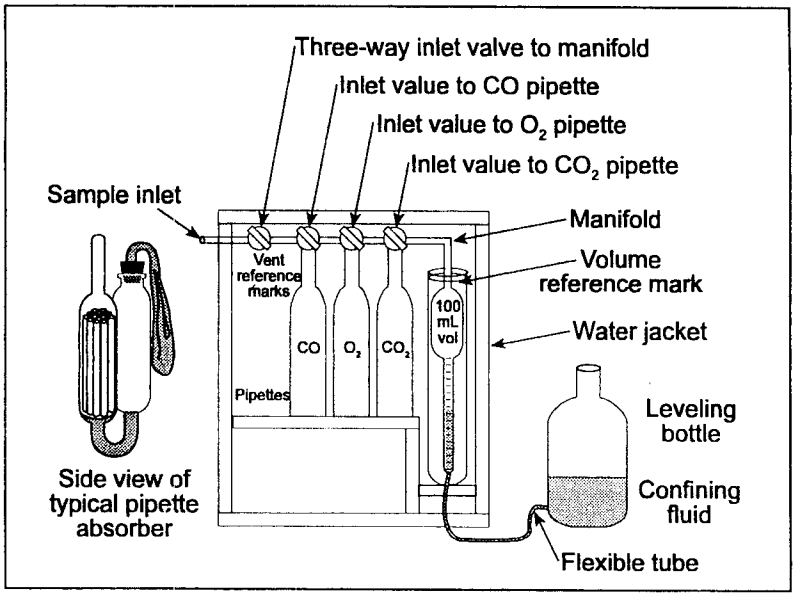

Figure 4-12. A typical Orsat analyzer for measuring $\%O_2$, $\%CO_2$, and %CO

In using the analyzer, a volume of sample gas is drawn into the measuring burette. This burette contains water, which is alternately forced in and out of the leveling bottle. The sample is alternately passed through tubes containing absorbing solutions. Potassium hydroxide is commonly used for absorbing carbon dioxide, alkaline pyrogallic acid for absorbing oxygen, and an acidic solution of cuprous chloride is used for absorbing carbon monoxide (although this part of the procedure is usually omitted).

The operation of the Orsat analyzer requires the learning of a straightforward but somewhat complicated technique. One must move the leveling bottle up and down to force the sample gas through the absorbing tubes. The reduction of gas due to the absorption is measured on the burette. The deft movements required in this method suggest that only those experienced in its use be permitted to perform it in a compliance source test.

Because of the water in the leveling bulb and the burette, the sample gas becomes saturated with water. The measurement, however, is a dry one, because the measurements are made by differences in level in the burette. Any contribution by water vapor cancels out.

Either grab or integrated sampling techniques may be used to obtain a Method 3 sample. Grab sampling is used when the gas composition is unstratified and doesn't vary over time. Here, a simple squeeze bulb draws a sample through a glass wool filter, which removes particulate matter, and passes it to the Orsat analyzer (Figure 4-13).

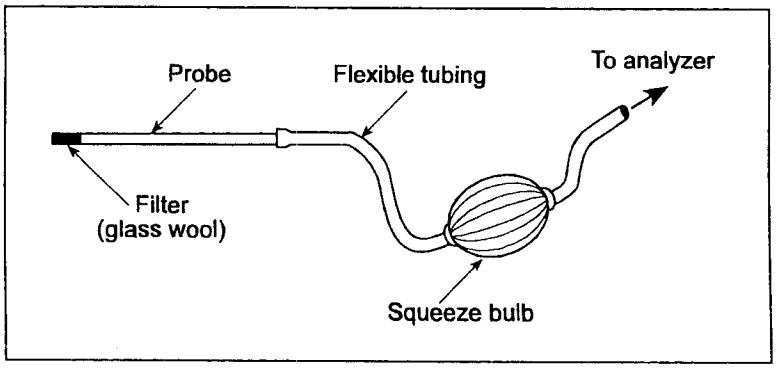

Figure 4-13. Grab sampling

In integrated sampling, a sample is drawn into a Mylar bag over a period of time. If the flue gas composition is fluctuating over that period, the bag sample will represent an average of that composition (Figure 4-14).

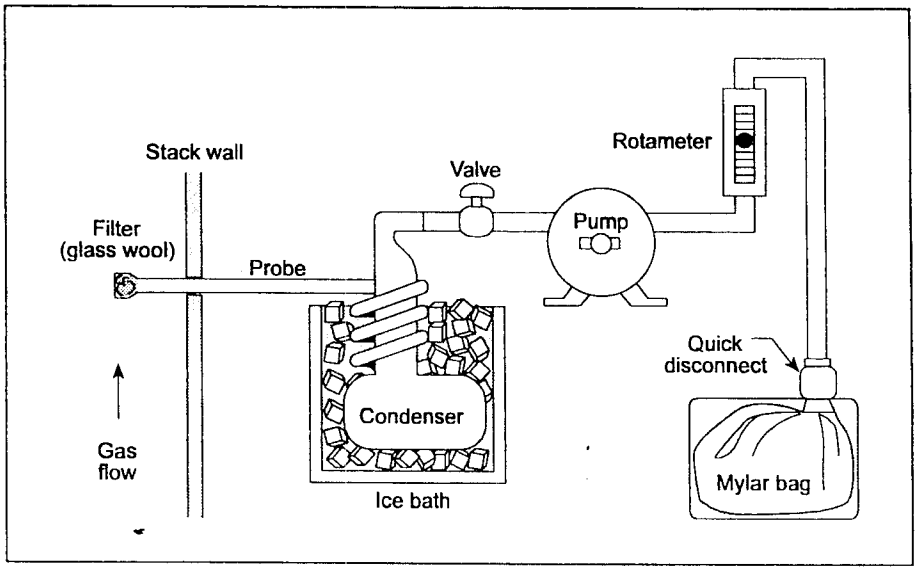

Figure 4-14. Integrated sampling

During integrated sampling, the probe can be stationed at one point or moved to multiple points. If the percent oxygen or carbon dioxide is required for an F factor emissions calculation, a multipoint integrated sample is required.

Today, the Orsat method has been largely supplanted by the use of analyzers. Method 3A allows the use of automated, instrumented techniques to determine the percentage of component flue gases. The instruments tend to be more accurate than the Orsat method since the ambiguities associated with proper technique are largely removed.

Method 4: Determination of the Moisture Content in Stack Gases

A determination of the moisture fraction, B_{ws}, is necessary in source sampling calculations. In the pitot tube equation, the wet molecular weight, M_s, is required in the calculation. In the isokinetic rate equation, both the dry and wet molecular weights, and the moisture fraction must be entered. The expression for the wet molecular weight is given in Eq. 4-6.

$$M_s = M_d(1-B_{ws}) + 18B_{ws} \quad (4\text{-}6)$$

The following four methods can be used to either estimate or measure the moisture content of the flue gas:

1. Saturation pressure
2. Psychrometry
3. Adsorption
4. Condensation

If the gas stream is saturated with water vapor, only a gas temperature measurement is necessary to determine the moisture content. At saturation, the gas is holding the maximum amount of water vapor possible for a given temperature. This information is well documented and one merely needs to measure the temperature and look up the moisture content in Table A-2 in the Student Workbook (saturated water vapor pressure).

If the gas stream is not saturated, a wet bulb-dry bulb technique can be used to estimate the moisture content. This is the same technique that is commonly used to determine the relative humidity in the ambient air and one which you may already be familiar with. This so-called **psychrometric technique** can be performed relatively easily by obtaining the wet bulb and dry bulb temperatures of the flue gas and then using a psychrometric chart or calculational methods to determine the moisture content.

The adsorption method is used for low moisture concentrations and can be quite accurate. By using a solid that has a high affinity for water vapor, the water can be adsorbed. Weighing the tube after adsorption and comparing it to its dry weight will give the amount collected. The method works well as long as the tube does not become saturated with water and the vapor breaks through. Silica gel tubes are used in the last impinger of the Method 5 train to trap the last traces of moisture from the flue gas.

The condensation method essentially distills the water out of the sample gas stream. By passing the flue gas through impingers submerged in an ice bath, the water condenses and collects

in the impingers. The volume of water collected can then be measured using a graduated cylinder, or the water can be weighed. The moisture content is then determined by dividing the volume of water collected by the total volume of gas collected (wet + dry).

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Knapp, K.T. 1976, October. The number of sampling points needed for representative source sampling. In L. Theodore (Ed.), *Proceedings of the Fourth National Conference on Energy and the Environment* (pp. 563-568). Dayton Section of the American Institute of Chemical Engineers.

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Chapter 5

The Source Test[1]

Source testing is used to determine compliance with emissions regulations and to provide information useful for evaluating control equipment efficiency or design, process economics, or process control effectiveness. Valid source sampling studies, therefore, yield valuable information to both the environmental control agency and to industry.

Each source test is, in a sense, an original scientific study, and should be organized and executed with the same care taken in performing any analytical test. This requires that objectives be decided before starting the test and that the procedures and equipment be designed to aid in reaching those objectives. After the test is completed, the results should be evaluated to determine whether the test objectives have been met.

Figure 5-1 outlines the procedures for planning and performing a basic Method 5 test.

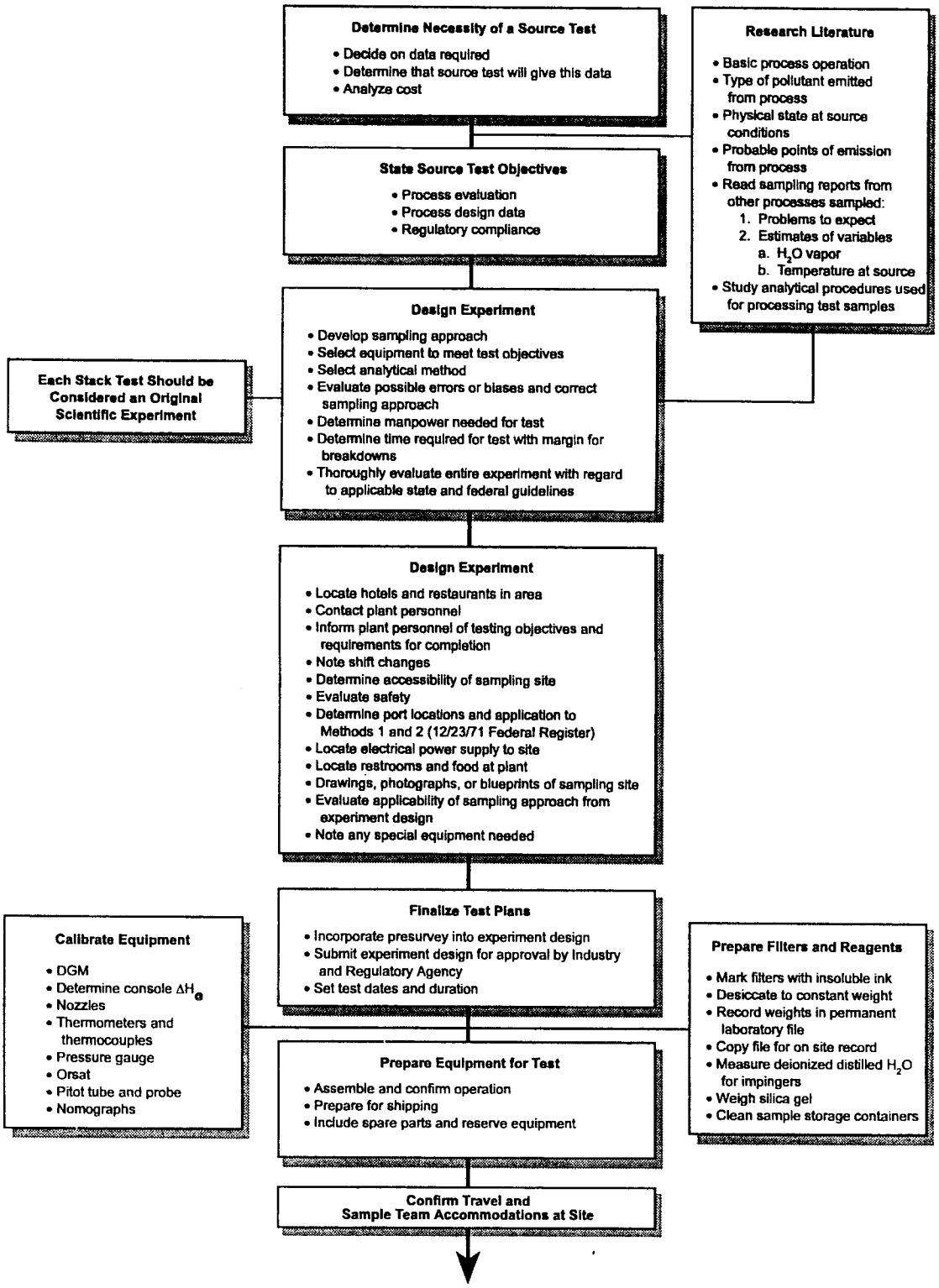

Figure 5-1. Planning and performing a Method 5 test

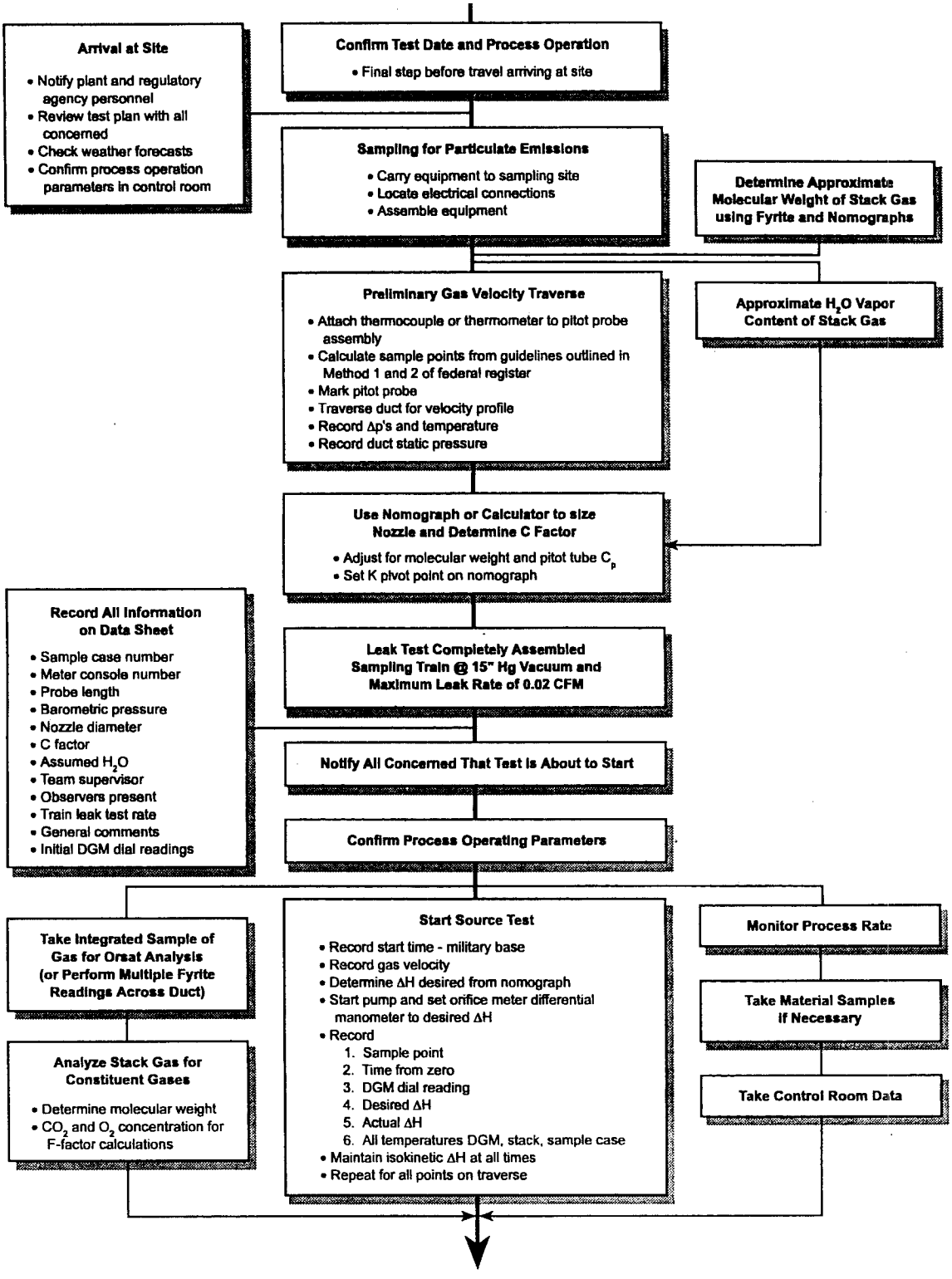

Figure 5-1. Planning and performing a Method 5 test (continued)

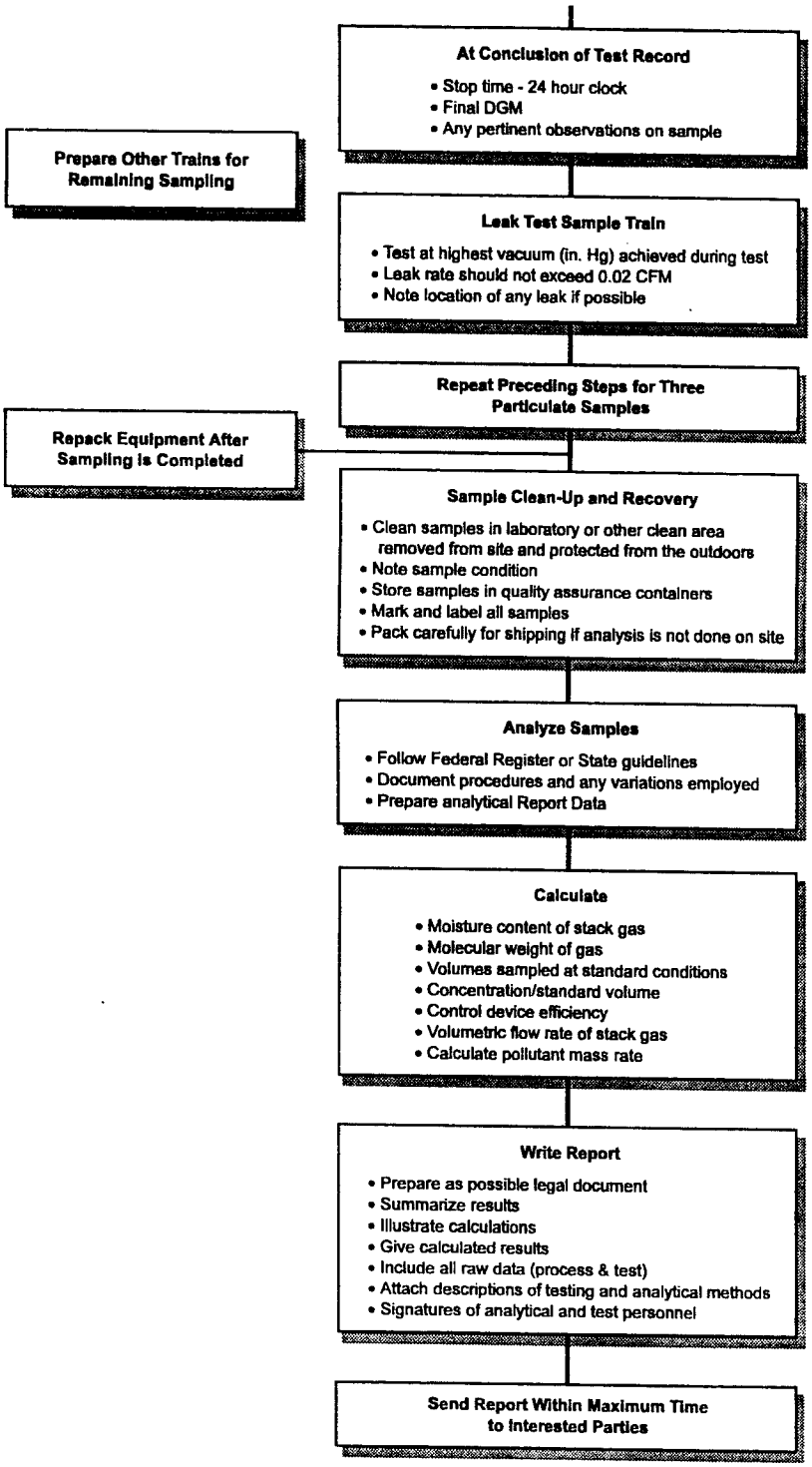

Figure 5-1. Planning and performing a Method 5 test (continued)

The Test Plans

The goal of most source tests is to measure a number of stack gas variables that are used in evaluating emissions source characteristics. The test plan should be developed using techniques and equipment specifically designed to provide complete and valid data relating to test objective. Approaching the study in this manner increases the possibility of obtaining a representative sampling of the source parameters evaluated.

Test Design

A well-designed test plan addresses sampling equipment, techniques, and analysis in an integrated procedure designed to meet the test objective. The source test must be based on a sampling technique that can collect the required data. The sampling equipment is then designed to facilitate the sampling procedure. After the sampling has been conducted, the analysis of the sample must be considered as an integral factor in the overall test design.

Developing a source test plan requires a knowledge of sampling procedures, and an understanding of the process operations at the facility being tested. The test plan clearly defines all aspects of the test program, and incorporates work done during pre-survey or other preliminary research studies. All aspects of this test plan, from the statement of objectives through analysis of the sample and results of the sampling, should be organized into a unified program. This program is then reviewed by the industrial or regulatory personnel involved. The protocol for the entire test procedure should be understood and agreed upon prior to the start of the test. A well-organized test protocol saves time and prevents confusion as the work progresses.

Test Equipment Preparations

The test equipment must be assembled and checked in advance. It should be calibrated following procedures specified in the Code of Federal Regulations. In these preparations, the entire sampling system should be assembled as intended for use during the sampling experiment. This ensures proper operation of all the components and points out possible problems that may require special attention during the test. This procedure will assist in making preparations and planning for spare parts. The equipment should then be carefully packed for shipment to the sampling site.

Sample Case Preparations

The sample case should be cleaned and checked thoroughly for needed repairs. All handles, brackets, clamps, and electrical connections must be inspected. Insulation in both the hot and cold areas must be in good condition. The sample case should not leak water from the melting ice into the filter heating compartment. The impinger section should have protective foam padding on the bottom and a good drainage system. The drain plug should be clean.

Calibrate the heater in the filter compartment to maintain a temperature around the filter of 120° ± 14°C (248° ± 25°F) or at other temperatures as specified in the Subparts of Title 40 of the Code of Federal Regulations. This calibration should be performed at several conditions (to account for seasonal weather changes) so that the filter compartment temperature

can be maintained at the proper level at all times. Often during sampling, the filter section is not easy to see; consequently, the filter temperature is difficult to monitor accurately. If the case is calibrated for several conditions, operators can control the temperature more closely.

All glassware, including the filter holder and frit, should be disassembled and cleaned. Individual glass pieces should be separated and checked for breaks or cracks. Pieces needing repair are cleaned after repairs have been made. A thorough glass cleaning for simple Method 5 testing is done with soap and water followed by a distilled water rinse. If analytical work is to be performed on the sample water condensed, clean the glassware by soaking in a methanol-basic hydroxide (NaOH or KOH) solution with pH 9. Glass should be left in the base solution until any stains can be easily washed away, but not longer than 48 hours since the solution can etch the glass. The basic solution should be rinsed away with distilled water. If ball-joint glassware is used, remove vacuum grease before cleaning with heptane, hexane, or another suitable solvent. Clean the glass frit by pulling several aliquots of nitric acid (HNO_3) through the glass frit with a vacuum pump. It should be rinsed at least three times with distilled water and dried before using. The rubber gasket surrounding the frit should be cleaned, removing any particles embedded in the rubber, which could prevent proper sealing. The frit and gasket must be constructed such that the glass filter mat does not become compressed in the sealing area.

Sampling Probe Preparation

A thorough probe check before a test helps prevent field problems. The sampling probe should be thoroughly inspected before field use. Remove the glass probe liner by loosening the union at the end of the probe. Completely disassemble the probe union and seal gasket, and inspect all the individual components.

Probe Sheath and Pitot Tubes

The stainless steel probe sheath should have a small hole drilled near the end of the probe. This prevents a pressure differential inside the sheath from possibly diluting the sample with air drawn down the probe. If the hole is not there, the probe end (fitted into the sample case) should be sealed airtight. Check the weld at the swagelok fittings for cracks and repair if necessary. Inspect the pitot tubes for damage and proper construction details (see pitot tube calibration section). Pitot tubes should be cleaned, checked for cracks or breaks, and securely fastened to the probe sheath to prevent accidental misalignment in the stack. All pitot tubes and components must be leak-tested.

Examine the union and seal gasket for wear. A stainless steel ring should be included in the union-gasket configuration for good compression and an airtight seal. If a rubber o-ring gasket is used (stack temperatures $\leq 350°F$), it should be inspected for wear and replaced if necessary. Asbestos string gaskets must be replaced each time the union-gasket is disassembled. After inspecting the glass liner-heating element, reassemble the probe in the following manner to prevent leaks.

1. Insert glass liner through probe and swage nut.
2. Place stainless steel ring over glass with flat side facing out.
3. Fit gasket over glass liner and push onto steel ring.

4. Align glass liner end with edge of swage nut closest to pitot tube orifice openings.
5. Screw the union on finger tight.
6. Use probe wrenches to tighten the union. If too much tightening is done here, the end of the glass liner will break.

Glass Liner - Heating Element

The glass liner should be thoroughly cleaned with a probe brush, acetone, and distilled water. If it will not come clean in this manner, it should be cleaned with dilute hydrochloric acid (HCl) or replaced. The glass liner-heating element in many sampling probes can not be separated, making thorough cleaning difficult. An easily separated liner-heater is a great advantage.

The heating element should be checked for good electrical insulation. The insulation on a frequently used probe liner-heating element will eventually be worn or burned away. This can expose frayed wires, which may short against the probe sheath. These hazards can be avoided with careful inspections and repair.

After thorough inspection, check the heating element in the reassembled probe. This procedure is helpful in finding problems before arrival at the sampling site. Attention should be given to the function of the electrical system and wrappings around the glass liner. These wrappings help prevent electrical shorts against the probe sheath while minimizing glass liner flexing that can cause a liner break or electrical short.

The Method 5 sampling train requires well identified, precut, glass mat filters that have been desiccated to a constant weight. Tare weights must be recorded to ensure against errors. Each filter should be inspected for pinholes that could allow particles to pass through.

The proper preparation of reagents is also an important pretest activity. The acetone (or other reagent) used to clean sampling equipment must be a low-residue, high-purity solvent and should be stored in glass containers. Silica gel desiccant should be dried at 250° to 300°F for two hours, then stored in airtight containers. It is a good procedure to use glass-distilled, deionized water in the impingers. Any other reagents should be carefully prepared.

All pertinent data on the reagents, tare weights, and volumes should be recorded and filed in the laboratory. Duplicates of this information should be provided for the sampling team leader.

Testing at the Source

The first step in performing the source test is to establish communication among all parties involved in the test program. The source sampling test team should notify the plant and regulatory agency of their arrival. All aspects of the plant operation and the test should be reviewed and understood by those involved. The proper plant operating parameters and test procedures should be recorded in a test log for future reference. The sampling team is then ready to proceed to the sampling site.

The flow diagram shown in Figure 5-2, which is an abbreviated form of Figure 5-1, outlines the procedures for performing the stack test.

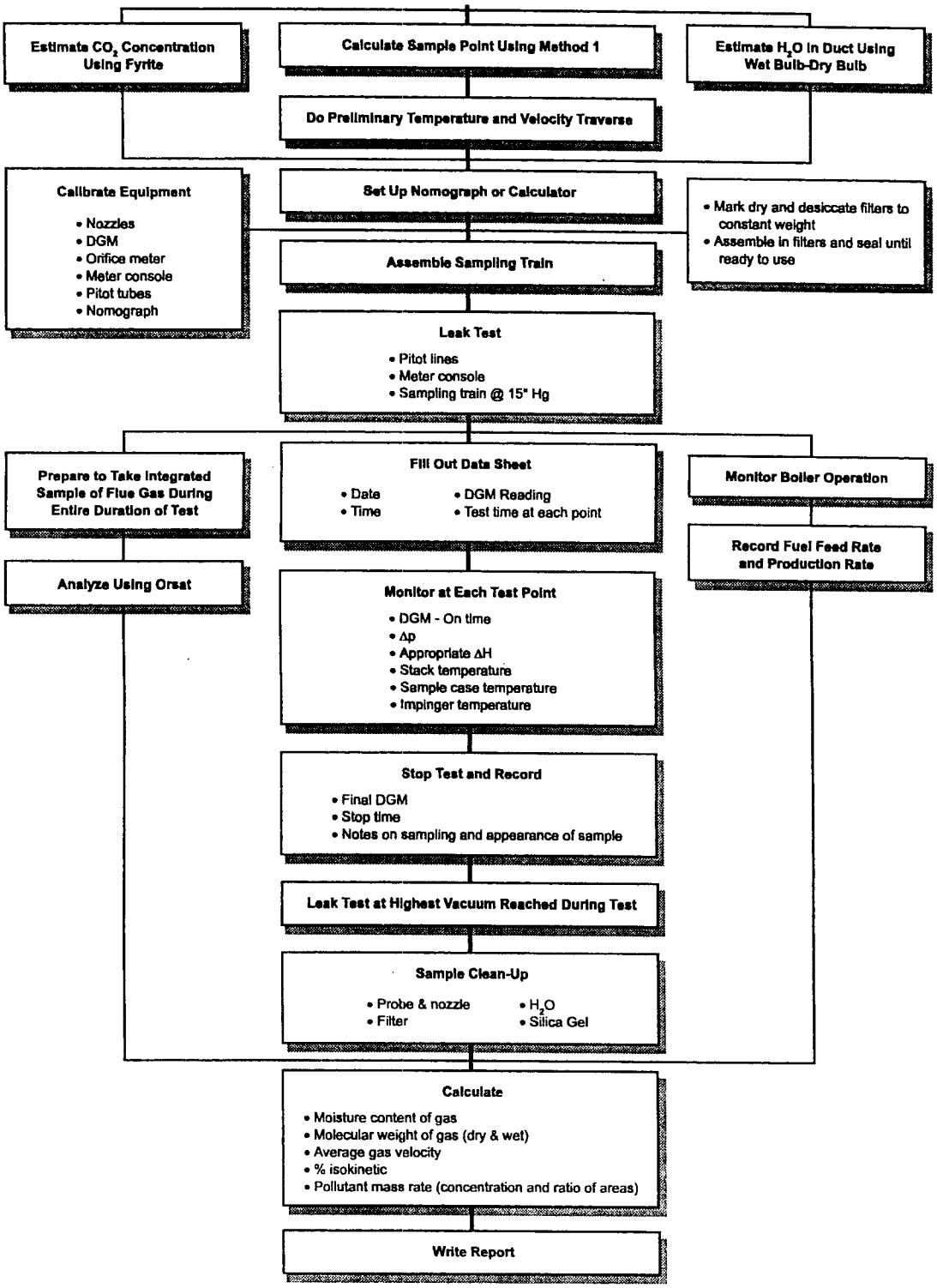

Figure 5-2. Performing a Method 5 test.

Preliminary Tests and Calculating

the Nozzle Diameter and the K Factor

Before assembling the Method 5 apparatus, the source tester must first select a nozzle of proper size and calculate the K factor in the isokinetic rate equation. Source variables used in solving the nozzle diameter and isokinetic rate equations should be determined. These equations may be solved using a nomograph, an electronic calculator, or a source sampling slide rule.

The principal variables that need to be determined are stack gas moisture content, average gas velocity pressure (Δp), stack gas temperature, and estimated average dry gas meter temperature. The stack gas moisture can be determined by Method 4 sampling or estimated with a wet bulb-dry bulb thermometer technique. The average Δp and stack gas temperature are determined by a preliminary stack traverse. The dry gas meter average temperature can be estimated to be 10°C (25°-30°F) greater than the ambient temperature at the site. These values are then used to find D_n and the K factor.

From Chapter 3, the nozzle diameter equation is:

$$D_n = \sqrt{\frac{0.0358 Q_m P_m}{T_m C_p} \frac{1}{(1 - B_{ws})} \sqrt{\frac{T_s M_s}{P_s \Delta p_{avg}}}} \qquad (5\text{-}1)$$

Where: Q_m can be taken at 0.75 cfm or any other desired flow rate

Once D_n is calculated, the source tester should select the nozzle in his/her toolbox that has a value closest to that calculated. After the selected nozzle is checked with calipers, the value of D_n is substituted into the isokinetic rate equation (Eq. 5-2):

$$\Delta H = \left[\underbrace{846.72 \; D_n^4 \Delta H_@ C_p^2 (1 - B_{ws})^2 \frac{M_d}{M_s} \frac{T_m}{T_s} \frac{P_s}{P_m}}_{K} \right] \Delta p \qquad (5\text{-}2)$$

Note: Most of the variables in the nozzle diameter and the isokinetic rate equation are known prior to sampling or can be closely estimated. Often, the solution to the equation can be partially calculated before the sampling with the few remaining variables inserted and the equation quickly solved on site.

The solution of the isokinetic rate equation, Eq. 5-2, using a calculator or computer, allows the tester to quickly and easily adjust the sampling rate for changes in the stack gas variables.

As discussed in Chapter 3, the commercially available nomograph is often used for the solution of the isokinetic rate equation. However, these nomographs have based the solution of the isokinetic rate equation upon the assumption that the pitot tube coefficient will be 0.84, the stack gas dry molecular weight will be 29.0 lb/lb-mole and will only vary with a change in stack gas moisture content. The nomograph also assumes that changes in other equation variables will be insignificant. Many purchasers are unaware of these assump-

tions or do not realize that manufacturer construction of the nomograph may be faulty. However, procedures have been developed to verify its accuracy.

Sample Case Preparations at the Sampling Site

The sample case is readied for sampling by filling the impingers with water and silica gel. Impingers 1 and 2 are each filled with 100 ml of water by inserting a funnel in the side arm and slowly pouring in the water. This makes it easy to displace air in the impinger and keeps the water from filling the bubbler tube. The third impinger is left dry. The fourth impinger is filled with 200-300 gm of preweighed silica gel. The silica gel must be added through the side arm. This prevents dust from collecting on greased ball joints or silica gel from being pulled up the center tube and out of the impinger.

After loading the impingers, securely fasten the U-joints. Attach the probe to the sampling case and secure the filter holder in position. Allow the filter compartment and probe to reach operating temperature. Leak-test the assembled train from the probe nozzle by pulling 380 mmHg (15 in.) Hg vacuum on the system. The maximum allowable leak rate is 0.00057 m^3/min (0.02 cfm). After the leak test, fill the impinger section with ice and allow time for all temperatures to stabilize.

Meter Console Operation

The meter console must be calibrated and thoroughly leak-tested prior to operation. Meter console operating procedures will differ somewhat according to manufacturer, however, the procedures discussed here will aid in operating most types of consoles.

When checking for leaks, the sample train is completely assembled as intended for use during the test. Turn on the probe and filter heating systems and allow them to reach operating temperatures. Disconnect the umbilical cord vacuum line and turn on the meter console pump. This allows the pump to lubricate itself and to warm up (this is especially important in cold weather). Leak-test the pitot tubes and lines during this warm-up.

The pitot tube impact pressure leg is leak-tested by applying a positive pressure. Blow into the impact opening until $\geq$ 7.6 cm (3 in.) H_2O is indicated by the differential pressure gauge. Seal the impact opening. The pressure should be stable for at least 15 seconds. The static pressure leg of the pitot tube is leak-tested in a similar way by drawing a negative pressure $\leq$ -7.6 cm H_2O. Correct any leaks.

Checking for Leaks

The sampling train is leak-tested when it has reached operating temperature. Turn off the console pump and connect the umbilical vacuum line. With the coarse control valve completely off, turn the fine adjustment (by-pass) valve completely counterclockwise. Plug the nozzle inlet and turn on the console pump. Slowly turn the coarse adjustment valve until it is fully open. Gradually turn the fine adjustment valve clockwise until 380 mmHg (15 in.) Hg vacuum appears on the vacuum gauge. If this vacuum is exceeded, do not turn the fine adjustment valve back counterclockwise; proceed with the leak test at the vacuum indicated or slowly release the nozzle plug and restart the leak test. At the desired vacuum,

observe the dry gas meter pointer. Using a stopwatch, time the leak rate for at least 60 seconds.

The maximum allowable leak is 0.00057 m^3/min. (0.02 cfm). Having determined the leak rate, slowly release the nozzle plug to bleed air into the train. When the vacuum falls below 130 mm (5 in.) Hg, turn the coarse adjustment valve completely off. If the leak test is unacceptable, trace all sections of the sampling train from the filter holder inlet back (i.e., leak-test from the filter inlet, then the first impinger, and so on) until the leak is found. Correct the leak and retest. Leak-test at the highest vacuum reached during the test after completing the sampling procedure. Testing for leaks should also be done any time the train is serviced (e.g., filter holder change). Record all dry gas meter readings and leak rates for each leak test.

Sample Train Operation

After the leak tests are completed, the sampling console should be prepared for sampling. The sampling console differential pressure gauges for the pitot tubes and orifice meter should be checked. Zero and level the gauges as required. If the console does not use oil manometers, the gauges must agree with an oil manometer within 5% for at least three Δp readings taken in the stack. This check should be done before testing. Oil manometers should be periodically leveled and re-zeroed during the test if they are used in the console.

The K factor of the isokinetic rate equation should already have been calculated. If not, it should be calculated at this point. After performing the calculation, the operator can then set up the sampling data sheet.

To start the test, first record the initial dry gas meter reading. Position the sampling train at the first sampling point, read the pitot tube Δp, and calculate the corresponding ΔH. Record the starting time of the test. Turn on the console pump and open the coarse sampling valve while simultaneously starting a stopwatch. Adjust the orifice manometer ΔH to the proper value using the fine adjustment valve. Check temperatures and record all data on the data sheet.

The sampling train should be moved to the next sampling point about 15 seconds before the time at the first point has elapsed. This allows the pitot tube reading to stabilize. The dry gas meter volume at the sample point is read when the stopwatch shows that the sampling time for that point has elapsed. The operator should quickly read the Δp and calculate ΔH for the next point, then set the proper sampling rate. Record all data and proceed as described for all points on the traverse.

At the end of the test, close the coarse valve, stop the pump, and record the stop time. Record the final dry gas meter reading. Remove the sampling train from the stack and test the system for leaks. Record the leak rate. After the train has cooled off, proceed to the clean-up area.

Clean-up

The clean-up and analysis of the sample taken with the Method 5 train is an integral part of the test. The careful operation of Method 5 sampling equipment must be complemented by a care-

ful clean-up of the train components. The flow chart (Figure 5-3) gives the general procedure for sample clean-up. Each step is presented with appropriate comments.

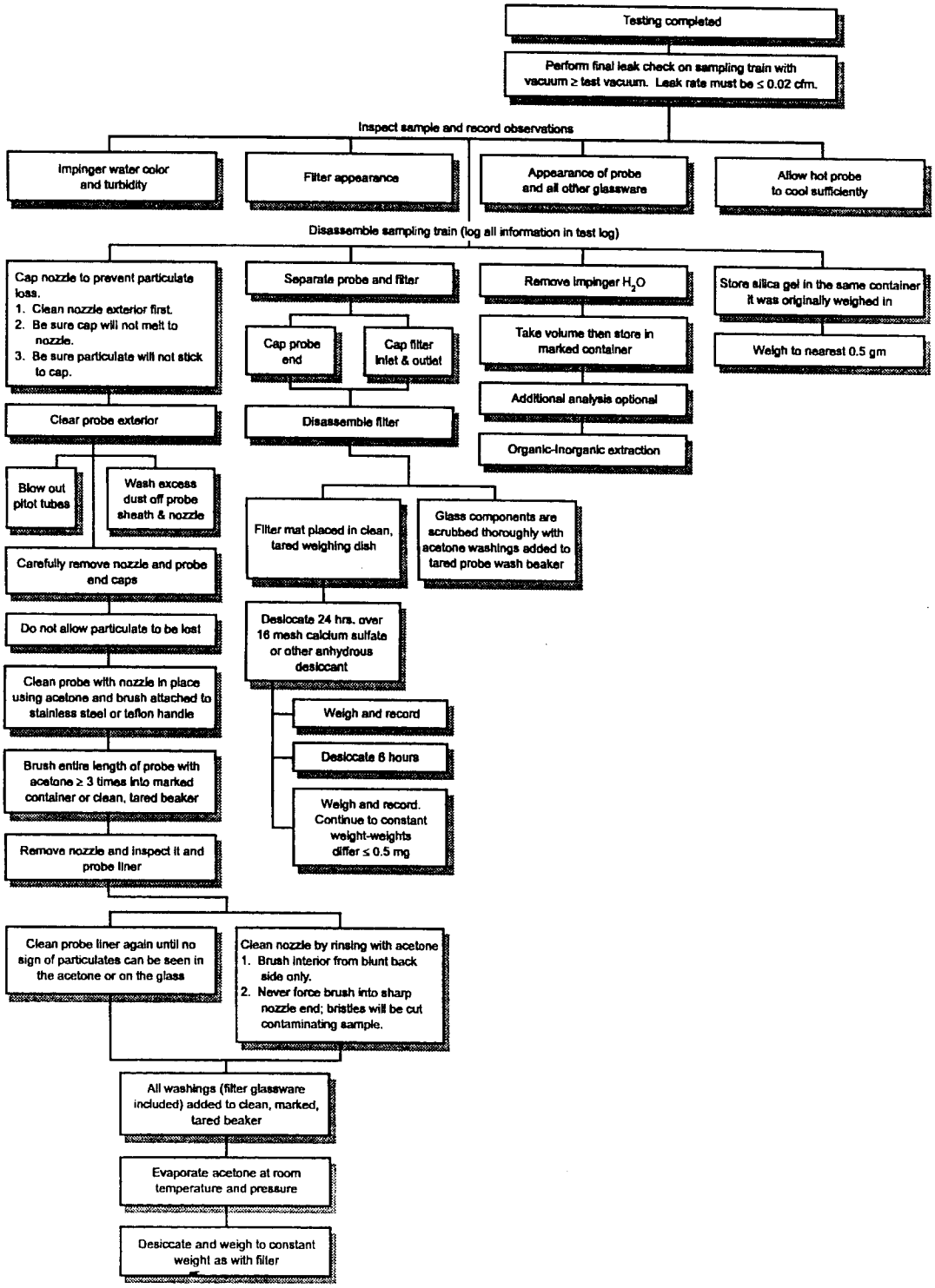

Figure 5-3. Cleaning the sampling train

Many factors can affect the accuracy of the final sample. Care and experience are very important when cleaning the sample train. A number of helpful tips are given below.

1. Always perform clean-up procedures in a clean, quiet area. The best area is a laboratory.
2. Make a probe holder for the probe cleaning procedure or be sure two people perform the procedure in order to prevent spills and accidents.
3. Clean all equipment in an area where an accidental spill may be recovered without contaminating the original sample.
   - Open and clean the filter holder over clean glassine or waxed paper so that a spill can be recovered.
   - Clean probe into a container sitting on the same type of glassine paper.
4. Clean the probe equipment thoroughly.
   - Brush the probe a minimum of three times.
   - Visually inspect the probe interior.
   - Record the appearance and confidence of cleanliness.
   - Repeat brushing until cleaning is complete.
5. Clean filter equipment thoroughly.
   - Brush all glassware until clean.
   - Check with tared cotton swab.
   - Remove all filter mats adhering to rubber seal ring. This is extremely important for accurate particulate weighing.
   - Do not scrape glass frit into sample.
6. The laboratory scale accuracy and sensitivity should be checked before each analysis using standard weights. Actual weight and scale reading should agree to $\pm$ 0.5 mg.
7. Careful labeling of all train components, tared beakers, and sample containers avoids problems and confusion.
8. Permanently marked weighing glassware with a permanent record of their new, clean, reference tare weight allows a check of cleanliness when tared just prior to use. This can also be helpful in checking any weighing discrepancies in the analysis (re-tare the glassware periodically).
9. Acetone is the solvent recommended for cleaning; however, water washing may be suggested by the type of pollutant sampled and should be added to the procedure if indicated.
10. Adding heat to the evaporation of solvent could evaporate volatile materials and give erroneous data.

The procedures illustrated in Figure 5-3 are only for cleaning the Method 5 train, although they are good general starting point procedures for cleaning any sampling train.

Analysis

Analysis of the sample using approved procedures and good laboratory technique provides accurate laboratory data. Good testing at the stack must be followed by accurate analysis in the laboratory so that valid data may be obtained.

For the weighing of particulate samples and the analysis of the impinger catch, the laboratory must have the following items.

- Analytical balance with minimum precision to 0.5 mg
- Large desiccating container that is airtight
- American Chemical Society reagent grade organic solvents
- Deionized, glass-distilled water.

When conducting the analysis, evaporate a control blank of 100 ml of each solvent used in any part of the analysis in a tared beaker at room temperature and pressure. Use only glass bottles and containers for all procedures that involve analytical work-up. Only silica gel may be stored in plastic containers.

Organic-inorganic extraction of the impinger may be required in determining emissions from some sources. Procedures are either specified for this other test method or in special guidelines provided by state or local environmental control agencies.

The most important aspect of cleaning and analyzing the Method 5 sampling train is the practice of good laboratory technique. The sampling team may not include an experienced chemist; therefore, good technique may have to be learned by all team members. If an experienced analytical chemist is a member of the sampling team, it would probably be best for the chemist to assist in cleaning the equipment.

Safety on Site

Source sampling is performed at a variety of industrial sites and under many different conditions. Adequate safety procedures may be different for any given situation; however, generally accepted industrial safety procedures should be helpful to source testers. The test team must be aware of safe operating methods so that alert discretion may be used for team safety at a particular sampling site. Safety is an attitude that must be instilled in all sample team members. Well thought out and implemented procedures will ensure the safety of all team members. It must be stressed that each team member is responsible for his/her own safety, as well as that of the other team members.

Key Factors in a Good Safety Program

Knowledge and experience are the major factors in formulating sound safety practice. An individual must draw upon these factors in determining safe methods. A knowledge of standard safety and operating procedures will permit their application in any situation. This basic knowledge in conjunction with understanding of the job tasks and possible dangers assists in planning preventive safety measures. Plans for operating at the job site may be developed around these procedures. Personnel should be informed of proper emer-

gency procedures and use of first aid, in case an accident occurs. Job experience and analysis of past accidents should be used in developing preventive safety programs.

Accident Analysis

The basic philosophy of a safety program should be that accidents are caused and, therefore, can be avoided or prevented. Accident analysis is a productive tool of this philosophy when it is used as a preventive step. This implies advance examination of a potentially hazardous situation to predict possible accidents and eliminate their causes.

Accident analysis is most effective when employed after an accident has taken place. The analysis procedure involves listing the major and contributing causes of the accident. If the real causes of the accident are analyzed in this manner, corrective action will suggest itself. Accident analysis should include preventive suggestions from people involved at the job site or those who have been previously injured.

Common Causes of Accidents

There are a number of common causes of accidents:

1. Failure of supervisory personnel to give adequate instructions or inspections. This includes information regarding job performance and safety requirements. Inspection of the job site is advisable before, during and after the job.
2. Failure of the person in charge to properly plan or conduct the activity. Experiment design and performance are important factors in success and safety of a stack test. This includes providing adequate manpower for the task.
3. Improper design, construction, or layout. Design aspects relate to equipment used and plan of operation.
4. Lack of protective devices or proper tools and equipment. "Jerry-rigging" and "making do" should only occur under unusual circumstances, not as standard practice.
5. Neglect or improper use of protective devices, job equipment, or materials.
6. Faulty, improperly maintained devices. Poorly maintained job equipment is inexcusable.
7. Failure on the part of any personnel to follow rules or instructions. Each individual is responsible for his/her own safety, as well as that of others. Personal disregard for safety rules jeopardizes the safety of all.
8. Personnel without adequate knowledge or training for performing job tasks. All present should be capable of performing the job tasks assigned. Trainees should be closely supervised.
9. Personnel in poor physical condition or with a poor mental attitude. These factors can affect the attitudes of other personnel toward each other, the supervisor, the task itself, or working conditions.
10. Unpredictable agents outside the organization. This may mean contract personnel who do not abide by standard rules or something as unpredictable as a biting insect or bad weather.

Accident Prevention

Preventing accidents during a stack test begins with advance planning. Familiarity with process operations and the site environment will give insight into chemical, mechanical, or electrical hazards that may be present. This knowledge will be useful in deciding on equipment to be used at the site. Knowledge of the weather conditions and logistical constraints further aid in establishing a safe test program. These items, in conjunction with evaluation of site safety and first aid facilities, will allow preparation of a source test.

The source test program will operate at peak efficiency and safety if plans are properly followed. Thorough planning, including contingency actions, eliminates the confusion that often contributes to accidents. This planning must include allotment of sufficient time for completion of the task, taking into account possible delays. Test personnel should be well-informed of the program procedures—their input for test performance and safety suggestions will be useful. Having once established an operating plan, all involved should adhere to it closely.

After thorough planning of the test program, attention focuses upon testing and safety equipment and on site operating practices. General comments on equipment preparation apply to both the sampling and safety equipment. Experimental design and personnel suggestions should indicate what equipment will be needed on the site for all functions. Equipment should be prepared and assembled in advance. It should be checked for suitable operation or potential problems. Equipment that could handle unexpected situations should also be included. Only necessary equipment should be taken to the site, where it should be used properly.

Work at the site must be organized following standard rules and the work plan carefully followed. Safety equipment should be used and personnel must remain alert to any changes on the site that could affect safe operation. All present should be made aware of any suspected problems.

The most important factor in any safety program is common sense. Common sense can, however, be an elusive element. Several steps presented in this section can help in developing sensible safety practices. Thorough advance planning and preparation for the jobs at hand begin the process of good safety practice. Informing involved personnel of all plans and using their suggestions about work safety increases the effectiveness of the planning. Analyzing a work situation for hazards, including past problems, into a coherent, organized safety program usually results in sensible and corrective procedures.

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Chapter 6

Report Writing[1] and Emissions Calculations

The report of a source sampling test presents a record of the experimental procedure and the test results. It is a written document describing a technical study and should state the objectives of the test, the procedures used to accomplish these objectives, results of the tests, and conclusions that can be drawn from the results.

The information should be presented in a clear, concise manner. The report must document all aspects of the test for follow-up quality control. Since the data may be used in litigation, sufficient data must be available to reconstruct all calculations, including those performed for calibrations. A suggested format for the report is given in this chapter, along with a brief explanation of each topic. A "quick reference" outline of the report format follows this section.

The Test Report

The test report should be presented as a professional document. It should be bound in an appropriate cover and contain a cover page giving the title of the report, the identity of the organization for which the test was performed, the organization performing the test, and the location and dates of the testing. Following the cover page is a signature page that is signed by all test participants, laboratory personnel, and supervisors. The signature page is essential for documentation and legal purposes. The following table of contents includes all topic listings and appendices with page numbers. An accurate table of contents is always appreciated by those reading the report.

Introduction

The report introduction briefly defines the purpose of the test. It includes a short description of the basic sampling method and of the process and control devices used. The introduction also states the testing location and date, along with the names of the test team personnel. The introduction should also identify industrial or regulatory agency personnel present on site during the test.

Summary of Results

The summary of test results is usually the first—and sometimes the only—section of the report that is read. For this reason, it is presented at the beginning of the report. The summary of results, which is a concise statement of test methods and results, is extremely important. It describes the sampling equipment used and the test methods employed. Standard methods are linked to state or federal guidelines, and any changes to the methods are tied to the sources used or to the regulatory agency that approved the changes. The source emission rate determined by the test is expressed in appropriate English and metric units. Comments concerning the process rate and continuity during the test are also given. State and/or federal regulatory emission rates are stated. The test summary should then give a conclusion about the test program and the results.

Process Description

A full description of the process is essential. Include the process description with any charts of process monitoring equipment (e.g., fuel feed rate, steam flow, materials produced) and samples of calculations used for determining production rate. Provide a flow diagram of the entire process with all pertinent information regarding production and control equipment. A full accounting of process operating conditions during the test should be included with these charts and diagrams. Specific attention must be given to the control equipment. State the manufacturer's name and operating specifications with notes on the operation of the device during the test.

Testing Methodology

A detailed description of the sampling scheme is given in this section of the report. Drawings, photographs, or blueprints of the stack or duct and sampling ports, including all dimensions actually taken by the test team, are required. These must be accompanied by a diagram showing the location of the sampling points within the duct and all important dimensions. Descriptions of the sampling and analytical procedures are required. The methods and specific equipment used should be stated and referenced. All modifications to standard procedures must be noted. Justification for these changes in addition to authorized approval from regulatory agencies or industrial personnel is necessary.

Results

The results portion of the report should allow easy access and review of summarized data. Present raw field and laboratory data in summary charts and tables with easily understood examples of the calculations made. Listing the results of these calculations in easy-to-read tables increases the value of this section.

Appendix

The appendix should include the following items:

- Test log (record of events at the site)
- Raw field data sheets (or signed copies)
- Laboratory report including raw data, tables, and calibration graphs

- Testing equipment listing:
  1. Design and manufacturer
  2. Calibration procedures and data sheets
  3. Serial numbers of equipment used in test
- Copies of the methods applied from CFR Appendix A, or other reference procedure outline
- Copies of applicable statutes and regulations concerning the testing

Quick Reference Outline for Report Writing

I. Presentation of report
   A. Suitable cover
   B. Cover page
      1. Report title
      2. Organization requesting test
      3. Organization performing test
      4. Location and dates of test
   C. Signature page
      1. Signatures of all test participants, laboratory personnel, and supervisors
   D. Table of contents

II. Report
   A. Introduction
      1. Test objectives
      2. Brief process and control equipment description
      3. Test dates and personnel
      4. Names of personnel
         a. Testers
         b. Observers
   B. Summary of results
      1. Brief test method identification
      2. Regulatory agency approval of method
      3. Comments on process operation
      4. Emission rate determined by the test
      5. Emission rate limit given by law

C. Process description

1. Describe process
2. Describe control equipment
3. Flow diagram of entire process
4. Charts and calculations of process production rates

D. Testing methodology

1. Sampling scheme with drawing and dimensions of site and sample points
2. Description of sampling method
3. Description of analytical method
4. Modifications to methods and approved justification

E. Results

1. Summary of data
2. Charts and tables
3. Example calculations

F. Appendix

Reporting in Units of the Standard: F Factor Methods

The use of the **F factor** in calculating particulate emission levels from new stationary sources was promulgated in the October 6, 1975 Federal Register. The F factor is intended to reduce the amount of data necessary to calculate particulate emissions in terms of the standard expressed as pounds per million Btu heat input (lb/10^6 Btu). As mentioned earlier, there are currently three types of standards for particulate mass:

1.	concentration standards	c_s	(ppm, gr/dscf, g/dscm)
2.	pollutant mass rate standards	pmr_s	(lb/hr, kg/hr)
3.	process rate standards	E	(lb/10^6 Btu, ng/J, lb/ton)

The emission rate, in terms of the units given in the New Source Performance Standards, is related to concentration and mass rate in the following manner:

$$E = \frac{pmr_s}{Q_H} = \frac{c_s Q_s}{Q_H} \quad (6\text{-}1)$$

Where: Q_s = the stack gas volumetric flow rate (units of ft^3/hr, m^3/hr)
Q_H = the heat input rate, the rate at which combusted fuel supplies heat to the boiler or other heat utilization system (Btu/hr, Kcal/hr)

By dimensional analysis, it can be seen that the units of E in terms of pollutant mass per unit of heat input are

$$E = \frac{lb/hr}{10^6 Btu/hr} = \frac{(lb/ft^3)\,(ft^3/hr)}{10^6 Btu/hr} = lb/(10^6 Btu) \quad (6\text{-}2)$$

To obtain emission rates in units of $lb/10^6$ Btu, it is necessary for the source sampler to obtain the following information:

1. Pollutant concentration, c_s
   a. Pollutant mass captured
   b. Dry gas volume sampled
2. Effluent volumetric flow rate, Q_s
   a. Stack gas velocity
   b. Stack temperature
   c. Stack pressure
   d. Dry gas composition (Orsat) $\%CO_2$, $\%O_2$, $\%N_2$
   e. Moisture content
3. Heat input rate, Q_H
   a. Fuel input rate
   b. Proximate analysis of fuel

Although all of the quantities for c_s and Q_s are obtained in a source test, the quantities making up the heat input rate, Q_H, may not be easily obtained. Once obtained, their accuracy may be in doubt since the source sampler usually is not able to calibrate or check the accuracy of the source fuel flow meter. The representative nature of the fuel sample and the accuracy of the fuel analysis itself may be difficult to determine. Consequently, factors based on simple principles of combustion were developed to avoid many of the problems involved in the calculation of E. By using the F factors, E may be obtained from a formula such as the following:

$$E = c_s F_d \left(\frac{20.9}{20.9 - \%O_2} \right) \quad (6\text{-}3)$$

Where: F_d is the dry F factor

The F factor essentially replaces the ratio Q_s/Q_H and the term in brackets is merely an excess air correction.

F factors are useful in calculating emissions for particulate matter. In the case of their application to continuous monitoring instrumentation for gases, it is even more valuable. The use of the F_d factor and its variants (F_c and F_w factors) in reporting continuous monitoring data in terms of lb/10^6 Btu heat input, enables the source operator to monitor only the pollutant gas concentration and the oxygen or carbon dioxide concentrations. Without this method, it would be necessary to continuously monitor stack gas velocity, temperature, fuel input rate, and so on. This would be possible, but impractical and expensive.

In the sections below, the derivation and uses of the F factors will be discussed further. Also, the requirements of 40 CFR 60.46 for the use of the F factors in Method 5 will be given.

Derivation of the F Factor Method

Before proceeding with the derivation of the F factors, it is necessary to give a few definitions used in combustion analysis, namely those for **proximate analysis, ultimate analysis**, and **gross calorific value**. The definitions generally apply to the fuel "as received" at the plant.

Proximate analysis is a fuel analysis procedure that expresses the principal characteristics of fuel as follows:

1. % moisture
2. % ash
3. % volatile matter
4. % fixed carbon

} Total 100%

5. % sulfur
6. Heating value (Btu/lb)
7. Ash fusion temperature

Ultimate analysis is the determination of the exact chemical composition of the fuel without paying attention to the physical form in which the compounds appear. The analysis is generally given in terms of percent hydrogen, percent carbon, percent sulfur, percent nitrogen, and percent oxygen.

Gross calorific value (GCV), also termed the "high heating value," is the total heat obtained from the complete combustion of a fuel, referred to a set of standard conditions. The GCV is obtained in the proximate analysis as the "heating value."

If one considers the volume of gas generated by the combustion of a quantity of fuel, the F factor relationship can be easily obtained. First, defining V_t as the theoretical volume of dry combustion products generated per pound of fuel burned in dscf/lb, the following equality can be made:

$$\frac{Q_s}{Q_H}(\text{excess air correction}) = \frac{V_t}{GCV} \qquad (6\text{-}4)$$

Dimensionally, this says

$$\frac{ft^3/hr}{Btu/hr} = \frac{ft^3}{Btu}$$

Q_s and Q_H can be determined at the source. V_t is obtained from the ultimate analysis of the fuel.

Remembering the first equation given in this section, Eq. (6-1)

$$E = \frac{c_s Q_s}{Q_H}$$

and substituting in Eq. (6-4),

$$E = \frac{c_s V_t}{GCV}\frac{1}{\left(\begin{array}{c}\text{excess air}\\ \text{correction}\end{array}\right)}$$

The quantity V_t/GCV is then defined as the F_d factor and the following simplified equation is obtained:

$$E = c_s F_d \frac{1}{\left(\begin{array}{c}\text{excess air}\\ \text{correction}\end{array}\right)} \qquad (6\text{-}5)$$

For Method 5, the oxygen concentration of the source must be determined simultaneously and at the same traverse. Since the excess air correction using percent oxygen is

$$\left(\frac{20.9 - \%O_2}{20.9}\right)$$

the equation to be used for calculating emissions for Method 5 is

$$E = c_s F_d \left(\frac{20.9}{20.9 - \%O_2}\right) \qquad (6\text{-}6)$$

As mentioned earlier, there are different types of F factors (see Table 6-1). The differences arise in the way in which the excess air corrections are determined. For example, the F_c factor is used when the percent CO_2 is determined instead of percent O_2. (*Note*: The F_c factor is not promulgated for use in calculating particulate emissions, although it may be used in reporting continuous monitoring data for gases.)

It should also be noted that the F factor method may be used with the percent O_2 and c_{ws} determined on a wet basis if the moisture content B_{ws} of the stack is known:

$$E = c_{ws}F_d\left(\frac{20.9}{20.9\,(1 - B_{ws}) - \%O_{2w}}\right) \qquad (6\text{-}7)$$

Note: The subscript w stands for measurements made on a wet basis. All other measurements are assumed to be made on a dry basis.

Table 6-1. F Factors.

Factor	Excess Air Units	Measurement Required for Emissions Determination	Calculations	Comments
F_d	$\frac{dscf}{10^6 Btu}$	$\%O_2$ (dry basis)	$E = c_s F_d\left[\frac{20.9}{20.9 - \%O_{2d}}\right]$	c_s determined on dry basis
F_c	$\frac{dscf}{10^6 Btu}$	$\%CO_2$ (dry or wet basis)	$E = c_s F_c\left[\frac{100}{\%CO_2}\right]$	c_s on dry or wet basis consistent with CO_2 measurement
F_w	$\frac{wscf}{10^6 Btu}$	$\%O_2$ (wet basis)	$E = c_{ws}F_w\left[\frac{20.9}{20.9\,(1-B_{wa}) - \%O_{2w}}\right]$	The "wet" F factor, c_{ws} and $\%O_2$ on wet basis B_{wa} = average moisture content of ambient air
F_o	———	———	$F_o = \frac{20.9F_d}{100F_c} = \frac{20.9 - \%O_2}{\%CO_2}$	Miscellaneous factor useful for checking Orsat data

Calculation and Tabulation of F Factors

The F_d factor method carries with it the assumption that V_t/GCV, the ratio of the quantity of dry effluent gas generated by combustion to the gross calorific value, is constant within a given category. This ratio, of course, is the F_d factor.

V_t is determined from the stoichiometry of the combustion reaction. If a hydrocarbon is burned in air, gaseous products will result; the volumes of which can be calculated. For example,

$$C_3H_8 + O_2 + N_2 \rightarrow CO_2\uparrow + H_2O\uparrow + N_2\uparrow$$

propane air gases

For each pound of fuel undergoing perfect combustion, a known amount of gaseous products will result. Using the stoichiometric relationships resulting from chemical reactions (similar to the preceding example) and given the gross calorific value of the fuel per pound, the following relationships have been developed for the F factors.

$$F_d = \frac{227.0\,(\%H) + 95.7\,(\%C) + 35.4\,(\%S) + 8.6\,(\%N) - 28.5\,(\%O)}{GCV} \quad \text{(metric units)} \tag{6-8}$$

$$F_d = \frac{10^6\,[3.64\,(\%H) + 1.53\,(\%C) + 0.57\,(\%S) + 0.14\,(\%N) - 0.46\,(\%O)\,]}{GCV} \quad \text{(English units)}$$

$$F_c = \frac{20.0\,(\%C)}{GCV} \quad \text{(metric units)} \tag{6-9}$$

$$F_c = \frac{321 \times 10^6\,(\%C)}{GCV} \quad \text{(English units)}$$

$$F_w = \frac{347.4\,(\%H) + 95.7\,(\%C) + 35.4\,(\%S) + 8.6\,(\%N) - 28.5\,(\%O) + 13.4\,(\%H_2O)}{GCV_w} \quad \text{(metric units)} \tag{6-10}$$

$$F_d = \frac{10^6\,[5.56\,(\%H) + 1.53\,(\%C) + 0.57\,(\%S) + 0.14\,(\%N) - 0.46\,(\%O + 0.21\,(\%H_2O))\,]}{GCV_w} \quad \text{(English units)}$$

If the source utilizes a combination of fossil fuels, a simple addition procedure can be used to compute the F factor.

$$F = xF_1 + yF_2 + zF_3 \tag{6-11}$$

Where: x, y, z = the fraction of total heat input derived from gaseous, liquid, and solid fuels, respectively

F_1, F_2, F_3 = the value of F for gaseous, liquid, and solid fossil fuels, respectively

Several F factors have been calculated for various types of fossil and waste fuels. It has been found that for a given type of fuel the F factor does not vary over a significantly large range. In general, it has been reported that the F_d factor can be calculated to within a ± 3% deviation and the F_c factor can be calculated to within a ± 5.9% deviation. The calculated factors are given in Table 6-2.

Table 6-2. F Factors for Various Fuels[1]

Fuel Type	F_d		F_w		F_c	
	dscm/j	dscf/10^6 Btu	wscm/j	wscf/10^6 Btu	scm/j	scf/10^6 Btu
Coal:						
Anthracite[2]	2.71×10^{-7}	10,100	2.83×10^{-7}	10,540	0.530×10^{-7}	1,970
Bituminous[2]	2.63×10^{-7}	9,780	2.86×10^{-7}	10,640	0.484×10^{-7}	1,800
Lignite	2.65×10^{-7}	9,860	3.21×10^{-7}	10,950	0.513×10^{-7}	1,910
Oil[3]:	2.47×10^{-7}	9,190	2.77×10^{-7}	10,320	0.383×10^{-7}	1,420
Gas:						
Natural	2.43×10^{-7}	8,710	2.85×10^{-7}	10,610	0.287×10^{-7}	1,040
Propane	2.34×10^{-7}	8,710	2.74×10^{-7}	10,200	0.321×10^{-7}	1,190
Butane	2.34×10^{-7}	8,710	2.79×10^{-7}	10,390	0.337×10^{-7}	1,250
Wood	2.48×10^{-7}	9,240			0.492×10^{-7}	1,830
Wood bark	2.58×10^{-7}	9,600			0.516×10^{-7}	1,920
Municipal Solid waste	2.57×10^{-7}	9,570			0.488×10^{-7}	1,820

[1] Determined at standard conditions: 20°C (68°F) and 760 mmHg (29.92 in. Hg)
[2] As classified according to ASTM D388-77
[3] Crude, residual, or distillate

Application of the F Factor to Method 5

In the Code of Federal Regulations, 40 CFR 60.46, under Test Methods and Procedures for the New Source Performance Standards (Table 6-3), emissions expressed in terms of lb/10^6 Btu are to be determined using the following formula:

$$E = c_s F_d \frac{20.9}{20.9 - \%O_2} \qquad (6\text{-}12)$$

Table 6-3. Test Methods and Procedures; 40 CFR 60.46

§ 60.46 Test methods and procedures.

(a) In conducting the performance tests required in § 60.8, the owner or operator shall use as reference methods and procedures the test methods in Appendix A of this part or other methods and procedures as specified in this section, except as provided in §60.8(b). Acceptable alternative methods and procedures are given in paragraph (d) of this section.

(b) The owner or operator shall determine compliance with the particulate matter, SO_2, and NO_x standards in § 60.42, 60.43, and 60.44 as follows:

(1) The emission rate (E) of particulate matter, SO_2, or NO_x shall be computed for each run using the following equation:

$E = C F_d (20.9) / (20.9 - \%O_2)$

E = emission rate of pollutant, ng/J (lb/million Btu).

C = concentration of pollutant, g/dscm (lb/dscf).

$\%O_2$ = oxygen concentration, percent dry basis.

F_d = factor as determined from Method 19.

(2) Method 5 shall be used to determine the particular matter concentration (C) at affected facilities without wet flue-gas-desulfurization (FGD) systems and Method 5B shall be used to determine the particulate matter concentration (C) after FGD systems.

(i) The sampling time and sample volume for each run shall be at least 60 minutes and 0.85 dscm (30 dscf). The probe and filter holder heating systems in the sampling train may be set to provide a gas temperature no greater than (160)14 °C (320)25 °F).

(ii) The emission rate correction factor, integrated or grab sampling and analysis procedure of Method 3B shall be used to determine the NO_x concentration ($\%O_2$). The O_2 sample shall be obtained simultaneously with, and at the same traverse points as, the particulate sample. If the grab sampling procedure is used, the O_2 concentration for the run shall be the arithmetic mean of all the individual O_2 sample concentrations at each traverse point.

(iii) If the particulate run has more than 12 traverse points, the O_2 traverse points may be reduced to 12 provided that Method 1 is used to locate the 12 O_2 traverse points.

(3) Method 9 and the procedures in § 60.11 shall be used to determine opacity.

(4) Method 6 shall be used to determine the SO_2 concentration.

(i) The sampling site shall be the same as that selected for the particulate sample. The sampling location in the duct shall be at the centroid of the cross section or at a point no closer to the walls than 1 m (3.28 ft). The sampling time and sample volume for each sample run shall be at least 20 minutes and 0.020 dscm (0.71 dscf). Two samples shall be taken during a 1-hour period, with each sample taken within a 30-minute interval.

(ii) The emission rate correction factor, integrated sampling and analysis procedure of Method 3B shall be used to determine the O_2 concentration ($\%O_2$). The O_2 sample shall be taken simultaneously with, and at the same point as, the SO_2 sample. The SO_2 emission rate shall be computed for each pair of SO_2 and O_2 samples. The SO_2 emission rate (E) for each run shall be the arithmetic mean of the results of the two pairs of samples.

(5) Method 7 shall be used to determine the NO_x concentration.

(i) The sampling site and location shall be the same as for the SO_2 sample. Each run shall consist of four grab samples, with each sample taken at about 15-minute intervals.

(ii) For each NO_x sample, the emission rate correction factor, grab sampling and analysis procedure of Method 3B shall be used to determine the O_2 concentration ($\%O_2$). The sample shall be taken simultaneously with, and at the same point as, the NO_xsample.

There are three points that should be made regarding application of the F factor to Method 5.

1. Only the dry F factor using percent O_2 for the excess air correction may be used in the calculation. The F_c and F_w factors may not be used.

2. The oxygen sample is to be obtained simultaneously with the Method 5 run at the same traverse points. This essentially requires that an additional probe be placed along with the Method 5 probe and an additional pump be used to obtain an integrated bag sample over the duration of the run. However, only 12 sample points are required. If there are more

than 12 traverse points determined by Method 1, an independent integrated gas sampling train could be used to traverse 12 points in the duct simultaneously with the particulate run.

3. The procedures in 40 CFR 60.46 apply to new fossil-fuel fired steam generators (new sources are those constructed or modified after August 17, 1971). For existing fossil-fuel steam generators, which are regulated by state standards, the state or local regulations should be checked for application of the F factor method.

Other Uses of F Factors

1. If values for Q_s, the stack gas volumetric flow rate, and Q_H, the heat input rate, are obtained during the source test, as they often are, several cross-checks can be made by comparing various calculated F factor values with the tabulated values. Equations that can be used to do this are as follows.

$$F_d\,(calc) = \frac{Q_s}{Q_H}\frac{(20.9 - \%O_2)}{20.9} \qquad (6\text{-}13)$$

$$F_w\,(calc) = \frac{Q_{sw}}{Q_H}\frac{20.9\,(1-B_{wa}) - \%O_{2w}}{20.9} \qquad (6\text{-}14)$$

$$F_c\,(calc) = \frac{Q_s}{Q_H}\frac{\%CO_2}{100} = \frac{Q_{sw}}{Q_H}\frac{\%CO_{2w}}{100} \qquad (6\text{-}15)$$

If, after calculating F_d, F_c, or F_w, a large discrepancy exists between the calculated value and the corresponding value in the table, the original data for Q_s, Q_H, and the Orsat data should be checked. This is an easy way of conducting a material balance check.

2. Using a tabulated value for F_d, F_c, or F_w and the data obtained during the stack test for Q_s and $\%O_2$, a value of Q_H may be obtained from the equations.

3. If ultimate and proximate analyses are available, they may be used to calculate an F factor using one of the equations. The calculated value can then be checked with the tabulated values and should be within 3 to 5% agreement, depending on the type of fuel and F factor.

The F_o factor is the ratio

$$F_o = \frac{20.9 F_d}{100 F_c} \qquad (6\text{-}16)$$

and is equal to

$$F_o = \left(\frac{20.9 - \%O_2}{\%CO_2}\right)$$

The $\%O_2$ and $\%CO_2$ are adjusted to a dry basis. A value differing from those tabulated would necessitate a recheck of the Orsat data.

Errors and Problems in the Use of F Factors

The following factors may contribute to errors in reporting emissions by using F factors:

- Deviations in the averaged or "midpoint" F factor value itself.
- Errors in the Orsat analysis and the consequent $\%O_2$ and $\%CO_2$ values.
- Failure to have complete combustion of the fuel (complete combustion is assumed in the derivation of all of the F factor methods).
- Loss of carbon dioxide when wet scrubbers are used affecting the F_d, F_c and F_w factors. Addition of carbon dioxide when lime or limestone scrubbers are used, affecting the F_c factor.

As stated earlier, the deviations in the F factors themselves have been found to vary no more than about 5% within a given fuel category. Since the F factors given are averaged values, differences in the ultimate analysis between fuel samples could easily account for the deviation. Also an error of a few percent in the oxygen concentration could cause a relatively large error in the value of E, or more importantly, could mean the difference between compliance and noncompliance. A recent publication by Mitchell and Midgett (1976) entitled "Field Reliability of the Orsat Analyzer," states

> The results from five collaborative tests of the Orsat method indicate that the use of Orsat data to determine the molecular weight of flue gases is a valid procedure, but the use of such data routinely to convert particulate catches to such reference conditions as 12% CO_2 and 50% excess air may introduce sizeable errors in the corrected particulate loading....
>
> However, since the use of Orsat data for calculating particulate conversion factors will likely continue, it seems prudent to develop procedures to check the reliability of Orsat data. One procedure, that could be instituted without affecting either the cost or time of a source test, would be to require that if the Orsat data is to be used for calculating a particulate conversion factor, then the integrated flue gas sample must be independently analyzed by at least two analysts and their results for each gas component must agree within a certain volume percent—say 0.3%—before they can be used to calculate the conversion factor.

Since the F factor method has been developed assuming complete combustion of the fuel, incomplete combustion will cause an error. However, if the %CO is determined in the flue gas, some adjustment can be made to minimize this error.

$$(\%CO_2)_{adj} = \%CO_2 + \%CO \qquad (6\text{-}17)$$

$$(\%O_2)_{adj} = \%O_2 - 0.5\ \%CO \qquad (6\text{-}18)$$

By making these adjustments, the error amounts to minus one-half the concentration of carbon monoxide present.

The loss of carbon dioxide in wet scrubbing systems will also have an effect on the F factors. A 10% loss of carbon dioxide will produce an approximate 10% error in the F_c factor. Since the F_d factor (oxygen correction) is based on source combustion products, its value will also be affected by the loss of carbon dioxide. If the gas stream has 6% O_2 and 1.4% carbon dioxide is lost in the scrubber, the error will be about +2.8%. The F_w factor is not applicable after a wet scrubber since the moisture content would have to be independently determined.

In general, the greatest errors associated with the F factor method are those that would be associated with the excess air correction. Collaborative testing programs have found that such errors can range as high as 35% when emission rates are corrected to 12% CO_2 using Orsat data. Considerable effort should be given by the source sampler to obtain representative and accurate Orsat data. The use of the automated Method 3A for the determination of oxygen and carbon dioxide should help to alleviate this problem.

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Chapter 7

Topics in Source Test Quality Assurance

The application of quality assurance techniques in source testing is central to obtaining test data that is accurate, precise, and complete. This chapter will discuss three topics in this area. The first topic, "error analysis," provides a background in the terminology associated with the evaluation of data. Types of error, accuracy, and precision are defined. The second topic, "role of the observer," discusses the functions of the source test observer who checks whether quality control methods are applied throughout the source test. The third topic, "calibration," details the calibration methods essential to obtaining good quality data.

Error Analysis

Introduction

The problem of accuracy in stack sampling measurements is considered and debated in almost every report or journal article that contains stack sampling data. There exists, however, a great deal of misunderstanding in the engineering community on the difference between error, precision, and accuracy. This misunderstanding often leads to a misinterpretation of analytical studies of stack sampling methods. The type of error analysis often used applies only to "randomly distributed error with a normal distribution about the true value."

It is the intention of this section to address the limitations of error analysis procedures so that experiments can be designed more carefully to yield results close to the "true" value.

Definitions

Error: The word "error" has two different meanings.

1. "Error" denotes the difference between a measured value and the "true" one. Except in a few trivial cases (such as the experimental determination of the ratio of the circumference to the diameter of a circle), the "true" value is unknown and the magnitude of the error is hypothetical. Nevertheless, this is a useful concept for the purpose of discussion.
2. When a number such as $\sigma = \pm 0.08$ is given or implied, "error" refers to the estimated uncertainty in an experiment and is expressed in terms of standard deviation, average deviation, probable error, or precision index.

Discrepancy: The term refers to the difference between two measured values of a quantity, such as the difference between those obtained by two students, or the difference

between the value found by a student and the one given in a handbook or textbook. The word "error" is often used incorrectly to refer to such differences.

Many beginning students suffer from the false impression that values found in handbooks or textbooks are "exact" or "true." All such values are the results of experiments and contain uncertainties. Furthermore, in experiments such as the determination of properties of individual samples of matter, handbook values may actually be less reliable than the student's because the student's samples may differ in composition from the materials that were the basis of the handbook values.

Random errors: Sometimes when a given measurement is repeated, the resulting values do not agree exactly. The causes of the disagreement between the individual values must also be causes of their differing from the "true" value. Errors resulting from these causes are called random errors. They are also sometimes called experimental or accidental errors.

Systematic or constant errors: If, on the other hand, all individual values are in error by the same amount, the errors are called systematic or constant errors. For example, all the measurements made with a steel tape with a kink will appear to be too small by an amount equal to the loss in length resulting from the kink.

In most experiments, both random and systematic errors are present. Sometimes both may arise from the same source.

Determinate and indeterminate errors: Errors that may be evaluated by some logical procedure, either theoretical or experimental, are called determinate, while others are called indeterminate.

Random errors are determinate because they may be evaluated by application of a theory that will be developed later. In some cases, random or systematic errors may be evaluated by subsidiary experiments. In other cases, it may be inherently impossible to evaluate the systematic errors, and their presence may be inferred only indirectly by comparison with other measurements of the same quantity employing radically different methods. Systematic errors may sometimes be evaluated by calibration of the instruments against standards. Whether the errors are determinate or indeterminate in these cases depends upon the availability of the standards.

Corrections: Determinate systematic errors and some determinate random errors may be removed by application of suitable corrections. For example, the measurements that were in error due to a kink in a steel tape may be eliminated by comparing the tape with a standard and subtracting the difference from all the measured values. Some of the random error of this tape may be due to expansion and contraction of the tape with fluctuations of temperature. By noting the temperature at the time of each measurement and ascertaining the coefficient of linear expansion of the tape, the individual values may be compensated for this effect.

Precision: If an experiment has few random errors, it is said to have high precision.

Accuracy: If an experiment has few systematic errors, it is said to have high accuracy.

Adjustment of data: This is the process of determining the "best" or what is generally called the most probable value from the data. If the length of a table is measured a number of times by the same method, by taking the average of the measurements we can obtain a value more precise than any of the individual ones. If some of the individual values are more precise than others, then a weighted average should be computed. These are examples of adjustment of data for directly measured quantities. For computed quantities, the process may be specialized and complicated.

Classification of Errors

Systematic Errors

1. Errors of calibration of instruments.
2. Personal errors. These are errors caused by the habits of individual observers. For example, an observer may always introduce an error by consistently holding his head too far to the left while reading a needle and scale having parallax.
3. Experimental conditions. If an instrument is used under constant experimental conditions (such as pressure or temperature) different from those for which it was calibrated, and if no correction is made, a systematic error results.
4. Imperfect technique. The measurement of viscosity by Poiseuille's law requires the measurement of the amount of liquid emerging from an apparatus in a given time. If a small amount of the liquid splashes out of the vessel that is used to catch it, a systematic error results.

Random Errors

1. Errors of judgment. Most instruments require an estimate of the fraction of the smallest division, and the observer's estimate may vary from time to time for a variety of reasons.
2. Fluctuating conditions (such as temperature, pressure, line voltage).
3. Small disturbances. Examples of these disturbances are mechanical vibrations or, in electrical instruments, the pickup of spurious signals from nearby rotating electrical machinery or other apparatus.
4. Definition. Even if the measuring process were perfect, repeated measurements of the same quantity might still fail to agree because that quantity might not be precisely defined. For example, the "length" of a rectangular table is not an exact quantity. For a variety of reasons, the edges are not smooth (at least if viewed under high magnification) nor are the edges accurately parallel. Thus even with a perfectly accurate device for measuring length, the value is found to vary depending upon where the "length" is measured on the cross-section.

Illegitimate Errors

These errors are almost always present, at least to a small degree, in the very best of experiments and they should be discussed in a written report. However, there are three

types of avoidable errors that have no place in an experiment, and the trained reader of a report is justified in assuming that these are not present.

1. **Blunders:** These are errors caused by outright mistakes in reading instruments, adjusting the conditions of the experiment, or performing calculations. These errors may be largely eliminated by care and by repetition of the experiment and calculations.

2. **Errors of computation:** The mathematical machinery selected for calculating the results of an experiment (such as calculators or computers) should have errors small enough to be completely negligible in comparison with the natural errors of the experiment. Thus if the data are accurate to five significant figures, it is highly improper to truncate these to three figures, and then to state "calculator error" as a source of error in the report. Such a calculation should be used for calculating the results of an experiment having only three or preferably two significant figures. On the other hand, if the experiment does give five significant figures, a more sophisticated calculator or computer should be used.

3. **Chaotic errors:** If the effects of disturbances become unreasonably large—that is, large compared with the natural random errors—they are called chaotic errors. In such situations, the experiment should be discontinued until the source of the disturbance is removed.

The Role of the Agency Observer[1]

Introduction

Air pollution control agency personnel who may not be directly involved in the compliance source sampling process are often called upon to evaluate source tests performed by environmental consultants or companies. Since emission testing requires that industry, at its own expense, contact highly skilled source test teams, the source test observer should be prepared to ensure that proper procedures are followed and that representative data are obtained.

The main purpose for the agency's observation of the compliance test is to determine that the test data are representative. There are other valid reasons to observe the test, such as establishing baseline conditions for future inspections. The major emphasis, however, is on the evaluation of the acceptability of the initial compliance test.

The seven steps an agency generally uses for establishing the compliance of a source with the agency's regulatory requirements are as follows.

1. **Familiarize:** The agency establishes contact with the source and becomes familiar with operations, emissions, and applicable regulations.
2. **Schedule source test:** This may be part of a compliance schedule of the New Source Performance Standards (NSPS).
3. **Establish methodology:** Testing requirements should be established and a testing plan developed by the agency.

1. Adapted from W.G. DeWees. 1982. *Supplemental Training Material for Technical Workshop on Evaluating Performance Tests.* DSSE, EPA, PEDco - Environmental Specialists.

4. **Final plan and test procedure development:** A presurvey should be conducted by a member of the testing team. A pretest meeting between the agency, source representative, and test team representative should be held to develop the final test plan.
5. **Actual compliance tests:** The facility operations and testing methodology are observed.
6. **Review of test data:** Compliance and official notification are determined.
7. **Continuing enforcement of compliance:** Follow-up inspections are undertaken, using data generated from source tests as a baseline for comparison purposes.

There are five areas where problems might develop in obtaining a sample representative of the source emissions. If a question arises as to the integrity of any one of these areas, the compliance test may be considered nonrepresentative. These five areas as follows.

1. The process and control equipment must be operated in such a manner as to produce representative values for stack emissions.
2. The sample port and point locations must be representative of the emissions.
3. The sample collected in the sample train must be representative of the sample points.
4. The sample recovered and analyzed must be representative of the sample collected in the sample train.
5. The reported sample results must be representative of the recovered and analyzed sample.

The source test to be monitored by the observer, then, is developed and conducted by the source test team and observer in four major phases: (1) preparing and planning, (2) conducting the test, (3) recovering, transporting, and analyzing the sample, and (4) submitting the report. Discussion of these phases follows.

Preparing and Planning

In the initial phase of preparation and planning, the agency must clarify for the source test team leader and process representative all the procedures and methods to be used during the entire testing program.

The review of the compliance test protocol submitted by the plant management or test consultant will explain the intended sampling plan to the observer. Two of the more important items to be checked are any deviations from standard sampling procedures and the proposed operations of the facility during the compliance test.

Many types of processes, sampling locations, and pollutants require some modification to the standard sampling procedure. The agency must determine if the modification will give equivalent and/or greater measurement results than would be obtained with the standard method.

The other major determination to be made from the test protocol is defining what constitutes normal operation of the facility. Example checklists for power plants and electrostatic precipitators are presented in Figure 7-1.

Example Checklist for Power Plants

8.1 Fossil Fuel Fired Indirect Heat Exchange

Checklist for process monitor

Monitor name _____ Test date _____
Facility representative _____
Company name _____
Designation of facility _____
Designation of unit being tested _____
Maximum heat input _____ million Kcal/hour
_____ million Btu/hour
Boiler nameplate capacity _____ pounds stream/hour
Electric generator capacity _____ megawatts
Induced draft fan capacity _____ CFM
at _____ in. H_2O and _____ °F.
Motor drive _____ hp.; amps _____; volts _____
Combustion control Automatic Hand
Type of soot blowing Continuous Period
Control of soot blowing
Automatic sequential
Hand
_____ time cycle
Describe the a.p.c. system _____

8.2 Monitoring Fuel During Test

Note: fuel feed measuring devices may be some distance from other instrumentation to be monitored.
Coal (classified by ASTMD 388-66)
Bituminous Sub-bituminous Anthracite Lignite
Coal feel measured by
Automatic conveyor scale
Batch weighing – dumping hoppers
Other (describe) _____
None
Liquid fossil fuel
Crude Residual Distillate
Liquid fuel feed measured by
Volumetric flow meter, make _____ model _____
Other (describe) _____
None
Gaseous fossil fuel
Natural gas Propane Butane
Other
Gaseous fuel feed measured by
Volumetric flow meter, make _____ model _____
Other (describe) _____
Other fuel (describe) _____
Other fuel feed measured by _____
_____

8.3 Fuel Input Data

Automatic weighing or metering

	Counter (totalizer) reading			
	Time	Coal	Oil	Gas
End test	____	____	____	____
Begin test	____	____	____	____
Difference				
Units fed during test	____	____	____	____
Counter conversion factor	____	____	____	____
Fuel per counter unit		____ tons	____ gal.	____ cu. ft.
Fuel fed during test		____ tons	____ gal.	____ cu. ft.
Fuel sampled during test				
Number of samples	____	____	____	
Total quantity of sample	____	____	____	
Date of last calibration of automatic metering device	____	____	____	

For manual weighing or other:
(Use this space for monitoring procedure and calculations)
_____
_____
_____

8.4 Fuel Analysis

Proximate analysis – as fired solid and liquid fuels

Component	% by weight	
	Typical	This test
Moisture		
Ash		
Volatile matter		
Fixed carbon		
Sulfur		
Heat value, Btu/lb		

or ultimate analysis – which includes the proximate analysis plus the following
Nitrogen _____
Oxygen _____
Hydrogen _____

Figure 7-1. Observer's checklist

Example Checklist for Power Plants

8.5 Monitoring Btu Input by Heat Rate of Boiler-Generator Unit and Kw-hr Output Meter when Applicable

Purpose is to serve as a check on other calculation procedures.
Boiler generator heat rate _____ Btu/kw-hr. Heat rate is obtained from facility representative. The heat rate curve is more accurate if corrections for super heat temperature, reheat temperature and condenser back pressure are applied for the test load condition.

Record data from generator output meter

	Time	Meter reading Kw-hr Output
End test	_____	_____
Begin test	_____	_____
Difference		
Kw-hrs. generated during test		_____

Btu input during test =
Kw-hrs. generated X heat rate (Btu/Kw-hr.)
Btu imput during test =
_____ x _____ = Btu

8.6 Monitoring Steam Generator Output By Steam Flow Meter

(Usually combined with air flow)

Steam flow measured by
Integrator on steam flow meter
Integrating chart from recorder
Calibration date _____
Primary purpose of stream flow monitoring is to indicate the load on the boiler during the test to observe and communicate to test team leader sudden significant change in stream flow which would be accompanied by significant changes in gas flow. Steam flow and flue gas flow changes parallel each other closely.

Record data by integrator on steam flow meter

	Time	Integrator	Reading
End test	_____	_____	_____
Begin test	_____	_____	_____
Difference			

Alternate factor _____
Total steam flow during test _____ pounds

Steam chart

Mark beginning and end of test runs on the steam chart and request a copy.
Chart marked and copy received.

8.7 Other Instrumental Data

Exhaust gas temperature just before the a.p.c. device
Max _____ °F Min _____ °F Avg _____ °F

Draft	Primary Collector	Secondary Collector
Before control device	_____ in. H_2O	_____ in. H_2O
After control device	_____ in. H_2O	_____ in. H_2O

Combustion recorders (indicate those available)
CO_2 Opacity
O_2 NO_x
SO_2
Obtain copy of recorders available and mark beginning and ending time of test.
· Soot blowing
Was soot blowing to be included in the test period
No Yes
If yes, record time and duration of soot blowing. _____
_____
· Special observations of any unusual operating condititons
_____
_____
_____

8.8 Electrostatic Precipitator - Checklist for Control Device Monitor

Parameters of design and operation affecting performance

Monitor name _____ Test date _____
Design efficiency _____

Rectifier power output	Design	During test
Voltage, kilowatts	_____	_____
Current, milliamps	_____	_____
Sparking rate, sparks/min	_____	_____
Gas volume, acfm	_____	_____
Gas velocity, fps	_____	_____
Gas temperature, °F	_____	_____
Fan motor, amperes	_____	_____
Electrical fields in direction of flow		_____
Number of rappers in direction of flow		_____

Other method of cleaning plates _____
_____
ESP rapping sequence
Normal _____
_____
During test _____
_____
Hopper ash removed sequence
Normal _____
Notes of unusual conditions during test
_____
_____
_____

Figure 7-1. Observer's checklist (continued)

Example Checklist for Power Plants

8.9 Scrubber - Checklist for Control Device Monitor

Parameters of design and operation affecting performance

Monitor name _____ Test date _____
Type of scrubber
Venturi Plate Other _____
Turbulent bed Spray
Design of efficiency _____

	Design	During test
Pressure drop across scrubber, in H_2O	_____	_____
Nozzle pressure, pounds/sq in.	_____	_____
Gas volume flow out of scrubber, cfm	_____	_____
Fan motor amperes	_____	_____
Liquid flow rate to scrubber gal/min	_____	_____
Liquid/gas rates, L/g	_____	_____
Recirculation of scrubbing liquid	_____	_____
Gas temperature of scrubber	_____	_____

Preconditioning or dilution air _____
During test _____
Rates of usual conditions during test _____

8.10 Fabric Filter - Checklist for Control Device Monitor

Parameters of design and operation affecting performance

Monitor name _____ Test date _____

Pressure drop across	Design	During test
Collector in H_2O		
Just after bag cleaning	_____	_____
Just before bag cleaning	_____	_____
Gas volume to bag house, acfm	_____	_____
Fan motor amperes	_____	_____
Type of cleaning		
Shaking - number of comparments		_____
Reverse air flow - number of compartments		_____
Repressuring - number of compartments		_____
Pulse jet (cleaned while on stream)		_____

Other _____
Cleaning cycle
Normal _____
During tests _____
Particulate removal sequence
Normal _____
During test _____
Notes of unusual conditions during test _____
Preconditioning or dilution air _____

8.11 Cyclone/Multicyclone - Checklist for Control Device Monitor

Parameters of design and operation affecting performance

Monitor name _____ Test date _____
Design efficiency _____

	Design	During test
Pressure drop across Collector in H_2O	_____	_____
Gas volume, acfm	_____	_____
Gas temperature °F	_____	_____
Fan moter amperes	_____	_____

Is the collector sectionalized with dampers for control of
Δp No Yes
If yes, how were dampers positioned during test? _____
Hopper ash removal sequence
Normal _____
During test _____
Notes of unusual conditions during test _____

Figure 7-1. Observer's checklist (continued)

The plant representative should understand and agree to all facility baseline conditions prior to the compliance testing, since the determination of representative operation of the

facility is for the protection of both the regulatory agency and the plant. The plant representative may suggest additional factors that could be considered as an upset condition that would not produce representative emissions.

The observer must be familiar with the process to be sampled. Whenever possible, the agency field inspector should be the observer for the process and control equipment. If the process is large or complicated, the observer may be aided by a process control engineer from the agency. An emission test run at the wrong process rating or without sufficient process data will not constitute a valid test. Familiarity with the specific process can be acquired through one or more of the many inspection manuals prepared by the Environmental Protection Agency for this purpose. These manuals indicate the methods and devices employed in monitoring process rates and/or weights.

Conducting the test

Some compliance tests may be routine enough that a pretest meeting on the morning before sampling begins will be sufficient to provide a complete understanding between all parties involved.

The review of the team leader's test protocol should have initiated the formulation of the observer's sampling audit plan. The observer's audit plan should contain the tentative testing schedule, facility baseline conditions preparation or modification of observer's checklist, and details for handling irregular situations that could occur during emission testing.

The sample testing schedule should allow the observer to plan his/her duties in a logical order and should increase his/her efficiency in obtaining all of the required data.

The observer's testing forms normally should need little modification. Any accepted modification to the normal sampling procedure should be covered by additional checks from the observer.

The observer should be prepared to handle any nonroutine situations that could arise during sampling procedures. A list of potential problems and their solutions should be made before the actual testing. The list should include minimum sampling requirements and process operating rates. The observer should also know who in his/her organization is authorized to make decisions that are beyond his/her own capability or authority.

The number of agency personnel observing the performance test must be adequate to ensure that the facility operation (process and control equipment) is monitored and recorded as a basis for present and future evaluations. The observing team should be able to obtain visible emission readings and transmissometer data for comparison with measured emission rates and should be able to ensure that the prescribed agency testing methodology was followed.

The plant representative should be available during testing to answer any questions that may arise about the process or to make needed process changes. It should be understood that, if any problems arise, all three parties—the test team, plant operators, and agency observer—are consulted. Since the observer may approve or disapprove the test, his/her intentions should be stated at the pretest meeting.

Before actually proceeding with the test, the observer should check the calibration forms for the specific equipment to be used. As a minimum, these forms should cover the following equipment:

Pitot tube

Nomograph (if used)

Dry gas meter

Orifice meter

If there is any question as to whether proper calibration procedures were followed, the problem should be resolved before initiating the test.

During the test, the outward behavior of the observer is of utmost importance. The observer should perform his/her duties quietly, thoroughly, and with as little interference and conversation with the source test team as possible. He/she should deal solely with the test supervisor and plant representative or have a clear understanding with them should it become necessary to communicate with the source test technicians or plant operators. Conversely, the observer should exercise caution in answering queries from the source test team technicians and plant operators directly and refer such inquiries to their supervisor. He/she should, however, ensure that sampling guidelines are adhered to and inform the test team if errors are being made.

Several checks must be made by the observer to ensure adherence to proper sampling procedures. To eliminate the possibility of overlooking a necessary check, an observer's checklist should be used for the sampling procedures and facility operation. An example of one of these checklists is included as Figure 7-2.

Sampling Checklists

8.12 General/Sampling Site

Stack/duct cross section dimensions _____
equivalent diameter _____
Material of construction _____ corroded? _____ leaks? _____
Internal appearance: corroded? _____
caked particulate? _____ thickness _____
Insulation? _____ thickness _____ lining? _____ thickness _____
Nipple? _____ I.D. _____ length _____ flush with inside wall? _____
Straight run before ports _____ diameters _____
Straight run after ports _____ diameters _____
Photos taken? _____ of what _____

Drawing of sampling location:

Minimum information on drawing: stack/duct dimensions, location and description of major discurbances and all minor disturbances (dampers, transmissometers, etc.) and cross sectional view showing dimentions and port locations.

8.13 Run Assembly/Final Preparations

(Use one sheet per run if necessary) Run # _____

Filter holder clean before test? _____
Filter holder assembled correctly? _____
Probe liner clean before test? _____ nozzle clean? _____
nozzle undamaged? _____
Impingers clean before test? _____
impingers charged correctly? Yes
Ball joints or screw joints? _____ grease used? _____ kind of grease _____
Pitot tube tip undamaged? _____
pitot lines checked for leaks? _____ plugging? _____
Meter box leveled? _____ pitot manometer zeroed? _____
orifice manometer zeroed? _____
Probe markings correct? _____ probe hot along entire length? _____
Filter compartment hot? _____ temperature information available? _____
impingers iced down? _____ thermometer reading properly? Yes
Barometric pressure measured? _____ if not, what is source of data _____
$\Delta H_@$ from most recent calibration _____
$\Delta H_@$ from check aginst dry gas meter _____
Nomograph check:
If $\Delta H_@$ = 1.80, TM = 100°F, $\%H_2O$ = 10%, P_r/P_m = 1.00,
C = 0.95 (0.55)
If C = 0.95, TS = 200°F, DN = 0.375, Δp
reference = 1.17 (0.118)
Align Δp = 1.0 with ΔH = 10; $_@\Delta H$ = 0.01, ΔH = 0.1 (0.1)
For nomograph set-up:
Estimated meter temperature _____ °F estimated
value of P_r/P_m _____
Estimated moisture content _____ % how estimated? _____
C factor _____ estimated stack temperature _____ °F
desired nozzle diameter _____
Stack thermometer checked against ambient temperature? _____
Leak test performed before start if sampling? _____
rate _____ cfm. @ _____ in. Hg

8.14 General/Sampling System

Sampling method (e.g., EPA 5) _____

Modifications to standard method _____
_____
Pump type: fibervane with in line oiler _____
carbon vane _____ diaphragm _____
Probe liner material _____ heated _____ entire length _____
Type S pitot tube? _____ other _____
Pitot tube connected to: inclined manometer _____
or magnehelic gauge _____
range _____ approx. scale length _____ divisions _____
Office meter connected to: inclined manometer _____
or magnehelic gauge _____ range _____
approx. scale length _____ divisions _____
Meter box brand _____ sample box brand _____
Recent calibration of orifice meter-dry gas meter? _____
pitot tubes _____ nozzles _____
thermometers or thermocouples? _____ magnehelic gauges? _____
Number of sampling points/traverse from Fed. Reg. _____
number to be used _____
Length of sampling time/point desired _____
time to be used _____

8.15 Sampling

(Use one sheet for each run if necessary) Run # _____

Probe-sample box movement technique:
Is nozzle sealed when probe is in stack with pump turned off? _____
Is care taken to avoid scraping nipple or stack wall? _____
Is an effective seal made around probe at port opening? _____
Is probe seal made without disturbing flow inside stack? _____
Is probe moved to each point at the proper time? _____
Is probe marking system adequate to properly locate each point? _____
Was nozzle and pitot tube kept parallel to stack wall at each point? _____
If probe is disconnected from filter holder with probe in the stack on a negative pressure source, how is particulate matter in the probe prevented from being sucked back into the stack? _____
If filters are changed during a run, was any particulate lost? _____
Meterbox operation:
Is data recorded in a permanent manner _____
are data sheets complete? _____
Average time to reach isokinetic rate at each point _____
Is nomograph setting changed when stack temperature changes significantly? _____
Are velocity pressures (Δp) read and recorded accurately _____
Is leak test preformed at completion of run? ___ cfm ____ ° ____ in. Hg
Probe, filter holder, impingers sealed adequately after test? _____
General content on sampling techniques _____
If Orsat analysis is done, was it: from stack _____
from integrated bag? _____
Was bag system leak tested? _____ was Orsat leak tested? _____ check against air? _____
If data sheets cannot be copied, record: approximate stack temperature _____ °F.
nozzle dia. _____ in. volume metered _____ ACF
first 8 Δp readings ____ ____ ____ ____ ____ ____ ____ ____

Figure 7-2. Sampling checklist

To understand the relative importance of the measurement of parameters of emission testing, the observer should know the significance of errors. A discussion of errors is given in a preceding section of this chapter.

Generally, it is best to have two agency observers at the source test. If only one observer is present, however, the following schedule should be followed.

For the first Method 5 run, when the facility is operating in the correct manner, the observer should go to the sampling site and observe the sample train configuration and the recording of the initial data. The observer should oversee the initial leak check (and the final post-test leak check). When the observer is satisfied with the sample train preparation, the test may be started. The sampling at the first port and the change-over to the second port should be observed. If satisfied with the tester's performance, the observer should go to a suitable point from the stack and read visible emissions for a six-minute period.

The facility operations must then be checked. This includes data from fuel flow meters, operating monitors, fuel composition, F factors, and so on. The data from continuous emissions monitoring equipment, such as opacity monitors and sulfur dioxide analyzers, should also be checked. This data will be useful in evaluating the Method 5 data. If the process and control equipment have operated satisfactorily and the data has been recorded as specified, the observer should make another visible emission reading for six minutes, then return to the sample site to observe the completion of the test. The final readings and the leak check after the completion of the test are two of the more important items to be checked. The transport of the sample train to the cleanup area and the sample recovery should then be observed.

If the observer is satisfied with all sampling procedures during the first run, the second run time will be spent observing the process monitors and checking the sampling team at the end of the sampling period. During the second run, two six-minute visible emission readings should be made with a check of the facility operations between readings. The observer should be satisfied that the facility data recorded are truly representative of the facility operations.

A visual observation of the particulate buildup on the filter and in the acetone rinse from the first two tests should be correlated to the visible emission readings or transmissometer data. This comparison of particulate collected will be valid only if the sample volumes were approximately the same. If the particulate catch on the filter and in the acetone rinse for the second test was consistent or greater than the visible opacity correlated to the first run, then the observer might need to spend more time overseeing the facility operations. If the second run, when correlated to the opacity, is less than the first test, more time might be spent in observing the emission test procedures for the third run.

Regardless of the main emphasis of the third run, the observer should still perform certain observations. The observer again should check all facility operations before testing. Two six-minute visible emission readings should be made with a check of the facility operation in between. The sample recovery of all tests should be witnessed, and the apparent particulate catch compared to the opacity readings. The observer can spend any additional time checking suspected weak points or problem areas.

Recovering, Transporting, and Analyzing the Sample

The observer should be present during sample recovery. It is imperative that the sample recovery and analysis be done under standard procedures. Each step should be thoroughly documented in case the results are used as evidence in court. (Courts have specific rules regarding evidence, which are contained in the Rules of Evidence.) Therefore, the observer should have a sample recovery checklist to ensure that all tasks have been performed properly.

To reduce the possibility of invalidating the results, all the particulate matter must be carefully removed from the sampling train and placed in sealed, nonreactive, numbered containers. It is recommended that the samples be delivered to the laboratory for analysis on the same day that the sample is taken. If this is impractical, the samples should be placed in a carrying case (preferably locked) in which they are protected from breakage, contamination, loss, or deterioration.

The samples should be properly marked to ensure positive identification throughout the test and analysis procedures. The Rules of Evidence require impeccable identification of samples, analysis of which may be the basis of future evidence. An admission by a lab analyst that he/she could not be positive whether sample 6 or sample 9 was analyzed, for example, could destroy the validity of an entire report.

Positive identification also must be provided for the filters used in any specific test. All identifying marks should be made before taring. Three or more digits should suffice to ensure the uniqueness of a filter for many years. The ink used for marking must be indelible and unaffected by the gases and temperatures to which it will be subjected. If any other method of identification is desired, it should be kept in mind that the means of identification must be positive and must not impair the function of the filter.

Finally, each container should have a unique identification to preclude the possibility of interchange. The number of a container should be recorded on the analysis data sheet associated with the sample throughout the test and analysis.

Samples should be handled only by persons associated in some way with the task of analysis. A good general rule to follow is "the fewer hands the better," even though a properly sealed sample may pass through a number of hands without affecting its integrity.

It is generally impractical for the analyst to perform the field test. The Rules of Evidence, however, require that a party be able to prove the chain of custody of the sample. For this reason, each person must document from whom the sample was received and to whom it was delivered. This requirement is best satisfied by having each recipient sign a standard chain-of-custody sheet initiated during the sample recovery.

To preclude any omissions of proper procedures after the sample recovery, the observer should have a sample transport and analytical checklist as shown in Figure 7-3.

General enviroment - clean up area _____
Wash bottles clean? _____ brushes clean? _____ brushes rusty _____
Jars clean? _____ acetone grade _____ residue on evap. spec. _____
Filter handled ok? _____ probe handled ok? _____
impingers handled ok? _____
After cleanup: filter holder clean _____ probe liner clean? _____
nozzle clean? _____ impingers clean? _____ blanks taken _____
Description of collected particulate _____
Silica gel all pink? run 1 _____ run 2 _____ run 3 _____
Jars adequately labeled? _____ jars sealed tightly? _____
Liquid level marked on jars? _____ jars locked up? _____
General comments on entire sampling project:

_____
_____
_____
_____
_____
_____
_____

Was the test team supervisor given the opportunity to read over this checklist? _____
Did he do so?
Observer's name _____ title _____
Affiliation _____ signature _____

Figure 7-3. Sample recovery checklist

Potential sources of error in the analysis may originate from contamination of the sample, or problems with the analyzing equipment, procedures, or documentation of results. Since the analysis is often performed at a lab distant from the plant site, the observer is often not present at the sample analysis. If there is any question in the observer's mind about the analyst's ability to adhere to good analytical practices in analyzing and in reporting data, the observer has two recourses: he may be present during analysis or he/she may require a certified laboratory. This is, however, an unnecessary burden and should not be done as a general rule.

During the analysis, any remaining portions of the sample should remain intact and placed in a safe place until the acceptance of the final report. Laboratory equipment, especially the analytical balance, should be calibrated immediately before the sample weighing. The laboratory data and calculations must be well documented and kept in such a manner that the agency can inspect the recording of any analysis upon request.

As noted in the lectures for this course, the observer should be aware of analytical tricks that can be used to bring a marginal test to within ± 10% of 100% isokinetic. Care should be taken that the values for the nozzle diameter and C_p do not change. Also, the weight of the impinger catch and the silica gel for the determination of B_{ws} should not be changed to accommodate a percent isokinetic value. It has been suggested that to ensure an unbiased test, the observer could supply the source tester with his/her own preweighed filter and preweighed amount of silica gel. Although extreme, this precaution may be necessary in special cases.

Submitting the Report

Upon completion of the compliance field test work, the observer can begin the final task of determining the adequacy of the compliance test data. He/she will be required to write

an observer's report for attachment to the source tester's report. The facility operation, the data, and the field checklists should provide the observer with sufficient information to determine the representativeness of the process and control equipment operation and the sample collection. All minimum conditions should have been met. If the observer suspects a bias in the results, this bias should be noted. A resulting bias that can only produce emission results higher than the true emissions would not invalidate the results if the plant were determined to be in compliance. Therefore, any bias that may occur should be listed along with the suspected direction of the bias.

The test team supervisor is responsible for the compilation of the test report and is usually under the supervision of a senior engineer who reviews the report for content and technical accuracy. Uniformity of data reporting will enable the agency to review the reports in less time and with greater efficiency. For this reason, a report format should be given to the test team supervisor along with the other agency guidelines.

The first review of the test report should be made by the observer. The observer should check all calculations and written material for validity. One of the greatest problems in compliance testing is in the calculation errors made in the final report. Several agencies have gone to the extreme of having the observer recalculate the results from the raw data to find any errors more easily. Errors should be noted along with comments by the observer. Although the conclusions in the observer's report are not the final authority, they should carry the greatest amount of weight in the final decision concerning the representativeness of the test.

Because of the importance of the observer's report and the possibility that it may be used as evidence in court, the observer should use a standard report format that will cover all areas of representativeness in a logical manner. An example of an observer's report format is presented as Figure 7-4.

Observer's Report Format

Cover
1. Plant name and location (Federal AQCR)
2. Source sampled
3. Date sampled
4. Testing firm
5. Control agency

Certification
1. Certification by observer(s)
2. Certification by author if not observer
3. Certification by key agency personnel

Introduction
1. Agency name
2. Purpose for observer's report
3. Purpose for test
4. Plant name, location and process type
5. Test dates
6. Pollutants tested
7. Applicable regulations
8. Agency sections and personnel directly involved

Summary of Representativeness of Data
1. Compliance test protocol
2. Calibration of sampling equipment
3. Process data
4. Control equipment data
5. Sampling procedures
6. Analytical procedures
8. Compliance test report

Facility Operation
1. Description of process and control device
2. Baseline conditions
3. Observer's facility data (checklists)
4. Representativeness of process and control device
5. Baseline conditions for agency inspector

Sampling procedures
1. Acceptability of sample port and point locations
2. Compliance test protocol
3. Calibration of sampling equipment
4. Observer's sampling data (checklist)
5. Representativeness of sampling
6. Observer's sample recovery data (checklist)
7. Representativeness of recovered sample
8. Observer's analytical data
9. Representativeness of sample Compliance

Test Report
1. Introduction
2. Summary of results
3. Facility operation
4. Sampling procedures
5. Appendices

Appendices
A. Copy of pertinent regulations
B. Related correspondence
C. Compliance test protocol
D. Observer's checklists
E. Observer's test log
F. Other related material

Figure 7-4. Observer's report format

In addition to the determination of representative data for the compliance test, the observer should report all conditions under which the facility must operate in the future to maintain its conditional compliance status. These conditions will be reported to the facility as conditions of its acceptance.

These reports and the conditions of the compliance acceptance will provide any agency inspector with sufficient data to conduct all future facility inspection trips.

Calibration

Source sampling equipment must be properly calibrated before it is used in the field. Systematic errors will result throughout the testing procedure as a result of uncalibrated or improperly

calibrated equipment. Without calibration, the stack tester cannot sample isokinetically in any source test, and he/she cannot correct the mass emission rate data if the equipment is calibrated after the test. It is therefore crucial that the apparatus used for stack testing be carefully checked. A manufacturer's calibration value or guarantee should not be trusted. It is not uncommon for a vendor to supply a miscalibrated apparatus. Also, with frequent use, instrument calibration values can change.

A careful source tester always double-checks his/her apparatus. Weeks of work may otherwise be questioned or may need to be redone. This section gives calibration procedures and design specifications for equipment commonly used in the source test. The procedures should be followed after receipt of new equipment and should be repeated after periods of extended use.

Calibration of the Source Sampling Meter Console

The gas meter and orifice meter of a sampling console may be calibrated during one procedure. The calibration described in this section may be performed using a standardized dry gas test meter or wet test meter. The sampling console must be thoroughly leak-tested before calibration.

Calibration Equipment

1. Calibrated test meter
   a. Wet test meter (correction factor should be 1.0 for wet test meter)
   b. Standardized dry gas test meter
2. Sampling meter console
   a. Dry gas meter
   b. Orifice meter
3. Stopwatch
4. Leak-free pump (fiber vane, preferably)
5. Vacuum tubing
6. Swagelok connections
7. Leak-test liquid

Meter Console Leak Test

The meter console pump, dry gas meter, and orifice meter must be leak-tested before calibration. This leak test can be accomplished by individually testing each piece of equipment or by leak-testing the entire assembly. The reference method suggests a procedure for leak-testing the assembled pump, dry gas meter, and orifice configuration (Figure 7-5). The following procedure, however, does not apply to diaphragm pumps.

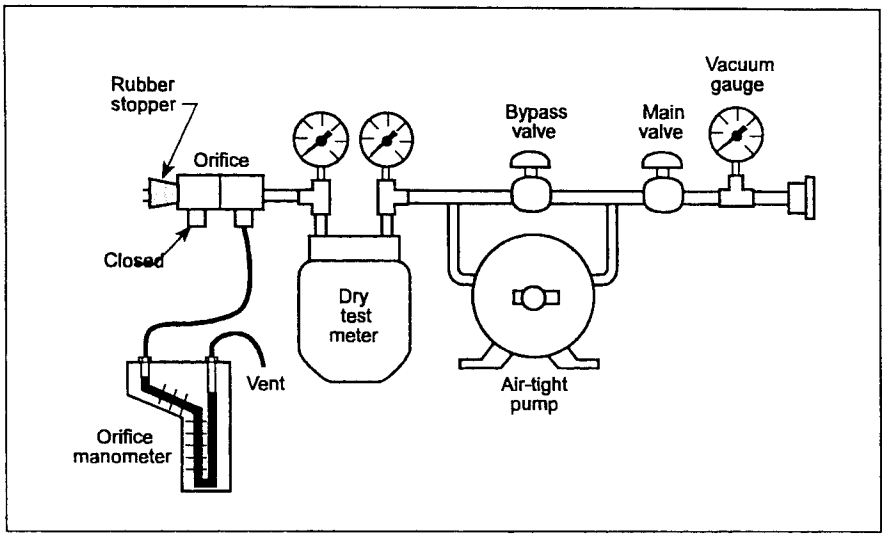

Figure 7-5. Leak check for the Method 5 meter console

1. Plug the orifice meter outlet with a one-hole rubber stopper that has a rigid tube through the hole.
2. Attach a length of rubber tubing (an in-line toggle valve in the tubing would be helpful).
3. Disconnect the static pressure side tubing of the orifice manometer and close off the tube. Leave the static tap of the manometer open to a vent position.
4. Completely open the bypass valve by turning it counterclockwise to a locked position; close the coarse adjustment valve.
5. Blow into the rubber tubing, plugging the orifice until the manometer shows a pressure differential greater than 6 in. H_2O.
6. Seal the tubing (close toggle valve). The manometer reading should remain stable at least 1 minute.
7. If a leak occurs, completely disconnect the orifice manometer and seal the orifice meter. Pressurize the system using a small pump and find the leak with a leak test solution.

Meter consoles with diaphragm pumps can be leak checked by pulling an air sample through a wet test meter-pump-dry gas meter setup. The leak rate should not exceed 0.0057 m^3/min (0.02 cfm).

Meter Console Calibration

The meter console calibration is accomplished with the equipment assembled as shown in Figure 7-6.

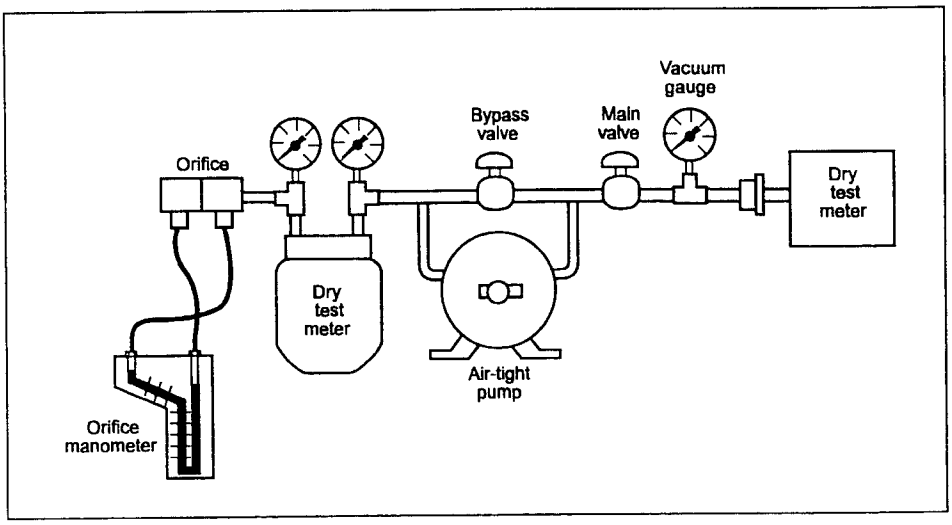

Figure 7-6. Meter console calibration assembly

The wet test meter should have a correction factor of 1. (A standardized dry gas meter may also be used to calibrate the meter console.) The calibration of the meter console dry gas meter and orifice meter is accomplished by passing a known volume of dry air through the test meter at a number of different pressure differentials on the orifice manometer.

In the calibration procedure:

1. Establish a pressure differential (ΔH) across the orifice meter with the pump and the coarse and fine adjustment valves.
2. Accurately record the dial readings for the wet test meter and dry gas meter while simultaneously starting a stopwatch.
3. Draw a predetermined volume of air (e.g., 5 ft^3) through the test meter. Record all temperatures during the calibration run.
4. Stop the pump when the predetermined volume has been reached on the wet test meter; simultaneously record the total elapsed time.
5. Make all calculations on the calibration form for this procedure (Figure 7-7).

Note: The standard temperature given by APTD-0576 (70° F) has been changed to 68° F, although the publication itself does not reflect this change.

Meter Console Calibration

Name _____ Date

Console no. _____ Dry gas meter no._____ Dry gas meter correction factor

Wet test meter no. _____ Correction factor

Barometric pressure, P_b_____in. Hg previous calibration and date

Orifice manometer setting ΔH, in. H_2O	Gas volume wet test meter V_w, ft^3	Gas volume dry gas meter V_d, ft^3	Temperatures				Time θ min	γ	$\Delta H_@$
			Wet	Dry Gas Meter					
			Meter t_w °F	Inlet t_{di}, °F	Outlet t_{do}, °F	Average t_d, °F			
0.5	5								
1.0	5								
2.0	10								
4.0	10								
6.0	10								
8.0	10								
						Average			

Calculations

ΔH	$\frac{\Delta H}{13.6}$	γ $\frac{V_w P_b (t_d + 460)}{V_d\left(P_b + \frac{\Delta H}{13.6}\right)(t_w + 460)}$	$\Delta H_@$ $\frac{0.0317\ \Delta H}{P_b (t_d + 460)}\left[\frac{(t_w + 460)\theta}{V_w}\right]^2$
0.5	0.0368		
1.0	0.0737		
2.0	0.147		
4.0	0.294		
6.0	0.431		
8.0	0.588		

γ = Ratio of accuracy of wet test meter to dry test meter. Tolerance= ± 0.02.

$\Delta H_@$ = Orifice pressure differential that gives 0.75 cfm of air at 68° F and 29.92 in. Hg. Tolerance = ± 0.15 in. Units given in in. H_2O

Orifice $\Delta H_@$ should fall between 1.59-2.09 in. H_2O, or modification may be necessary for some sampling situations.

Figure 7-7. Form for meter console calibration

Calibration of Temperature Measurement Devices

The Method 5 source sampling system requires gas temperature measurements at several locations. The temperature measurements are important for correcting stack gas parameters to standard conditions. Accurate measurement within the tolerance given in the Code of Federal Regulations is essential. Procedures are given here for calibrating general types of temperature sensor devices. Manufacturer recommendations for special temperature sensors should be followed carefully.

Temperature Reference

A commercially available mercury thermometer capable of ± 1° sensitivity is sufficient for calibration purposes. The thermometer should be immersible in ice water, boiling water, hot mineral oil, or a tube furnace. The thermometer scale should cover the range of anticipated source temperatures.

Bimetallic Thermometer Calibration

Dial or bimetallic thermometers are used for temperature measurement in several train locations. Adjustable dial thermometers are calibrated by immersion in a water bath along with the mercury thermometer. Temperature readings should be taken at several points on the dial thermometer scale, and its reading should be set to correspond with the corrected mercury thermometer measurement (adjusted for elevation above sea level). Non-adjustable dial thermometers must agree with the corrected mercury thermometer temperature within 3°C (5.4° F), if used at the filter heater compartment, and within 1°C (2° F) when used at other locations in the sampling train.

It is unlikely that a dial or a bimetallic thermometer would be used to monitor in-stack gas temperature at most sources. If either is used for stack measurements, it must be calibrated to read stack temperature to within 1.5% of the minimum absolute stack gas temperature.

Thermocouples

An electromotive force is produced when two connected, dissimilar metal wires are subjected to temperature variations. The electromotive force (EMF) is fixed for a given combination of metals and is proportional to the temperature of the metal wires at the measurement junction. A cold or reference junction is maintained at the metering device. Potentiometers or millivoltmeters are commonly used to measure EMF. The voltage signals are, today, usually converted to read directly in degrees on either an analog or digital meter.

Thermocouple wires are necessarily thin to speed response time and increase EMF sensitivity. They must be thoroughly inspected on a routine basis. Any frayed or damaged wire should be replaced or repaired. Insulation must be complete, or wires could short against metal surfaces. The thermocouple junction should be either welded or silver-soldered.

The thermocouple should be calibrated with the millivoltmeter that will be used in the field. The voltmeter should first be zeroed and calibrated according to the manufacturer's instructions. The following procedure should then be followed:

1. Connect the meter to the thermocouple.
2. Check the thermocouple reading with that of a mercury thermometer at several readings:
   a. Boiling water
   b. Ice point
   c. Ambient air

If the temperature at the stack is greater than that of boiling water, several calibration points across the anticipated temperature range should be made. This may be done by using hot mineral oil, a tube furnace, or another apparatus that allows thermocouple and mercury thermometer comparison. The thermocouple should be thoroughly cleaned after it is calibrated in a material such as mineral oil. Do not immerse ceramic-covered thermocouples in a liquid calibration medium. They absorb the liquid, which can affect reading during calibration or in field use.

3. Record the data (Figure 7-8).
4. Make the proper adjustments (if possible) on the voltmeter to read the proper temperatures.
5. If the meter cannot be adjusted to reflect the proper temperatures, construct a calibration curve and include it in your field notebook.

Temperature Calibration

Name _____ Date _____

Barometric Pressure _____ Land Elevation _____

Ice Bath

Hg in Glass Thermometer Temperature				Corrected Hg in Glass Temperature				Temperature Device _____ Identification No. _____ Temperature			
°C	°K	°F	°R	°C	°K	°F	°R	°C	°K	°F	°R

Boiling Water Bath

Hg in Glass Temperature				Corrected Temperature				Device _____ No. _____			
°C	°K	°F	°R	°C	°K	°F	°R	°C	°K	°F	°R

Mineral Oil Bath

Point	Hg in Glass Temperature				Corrected Temperature				Device _____ No. _____			
	°C	°K	°F	°R	°C	°K	°F	°R	°C	°K	°F	°R
1												
2												
3												
4												

Figure 7-8. Form for temperature calibration

Calibration of the Type S (Stausscheibe) Pitot Tube

The Type S pitot tube has several advantages as a gas velocity pressure measurement instrument in particulate-laden gas streams. The Type S tube is compact. Separately or attached to a sampling probe, the tube fits easily into a 3-in. diameter sampling port. The Type S pitot tube maintains calibration in abusive environments, and its large sensing orifices minimize plugging by particulates. The Type S pitot tube also gives a high manometer reading for a given gas velocity pressure, which is helpful in stacks with low gas velocity. These features make the Type S pitot tube the most frequently used source sampling pitot tube.

The Type S pitot tube construction details should be carefully checked before calibration. The tube should be made of stainless steel or quartz (for high temperature gas streams) with a tubing diameter (D_t) between 0.48 and 0.95 cm (3/16in. 3/8in.). The distance from the base of each pitot tube leg to the plane of the orifice opening (P_A,P_B) should be equal (Figure 7-9).

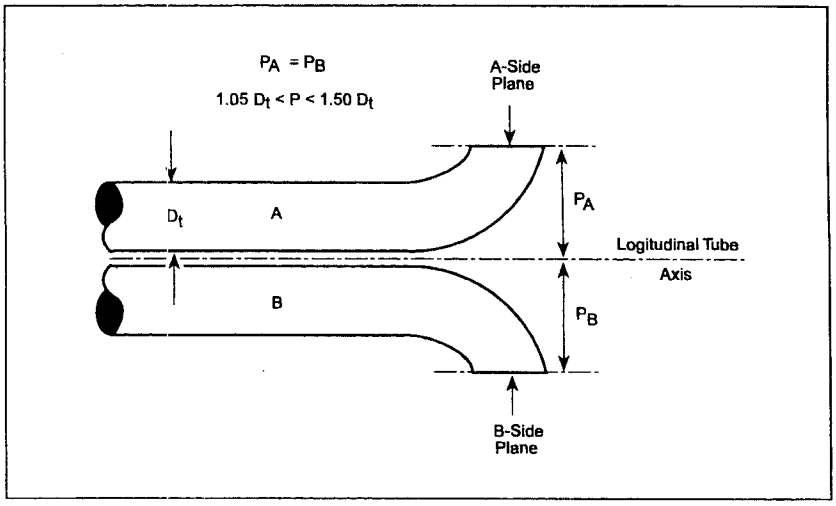

Figure 7-9. Type S pitot tube leg alignment

P_A and P_B should be between 1.05 and 1.50 times the tubing diameter. Pitot tube orifice face openings should be properly aligned as shown in Figure 7-10. Misalignment of these openings can affect the pitot tube calibration coefficient and should be corrected before calibration.

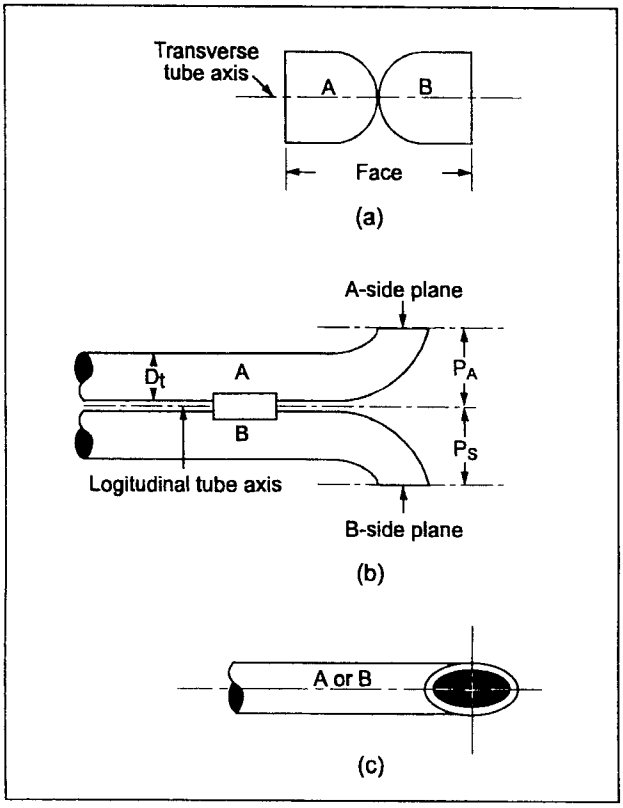

Figure 7-10. Type S pitot tube orifice alignment

Calibration Equipment

1. Type S pitot tube assembled in the configuration anticipated for sampling. Both legs A and B permanently identified.
2. Inclined manometer with a sensitivity to 0.13 mm (0.005 in.) H_2O.
3. Standard pitot tube
   a. Standard pitot-static tube with NIST (National Institute of Standards and Technology) traceable calibration coefficient.
   b. Standard pitot-static tube constructed as shown in Figure 7-11. A pitot tube design according to these criteria will have a baseline calibration coefficient of 0.99 ± 0.01.

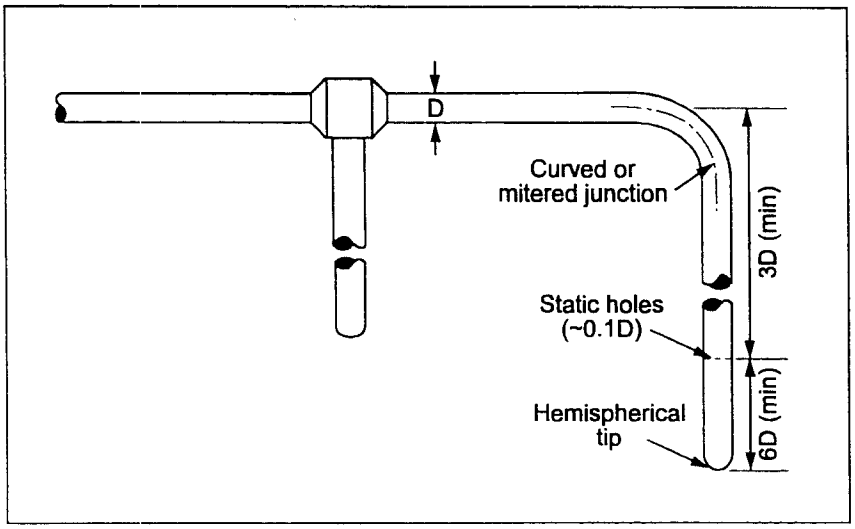

Figure 7-11. Standard pitot static tube

4. Calibration duct
   a. Minimum duct diameter cross-section of 30.5 cm (12 in.)
   b. Cross-section constant over a distance greater than 10 duct diameters
   c. Entry ports arranged so that standard pitot and Type S pitot are reading gas pressure at the same point in the duct
   d. Flow system capable of generating a gas velocity of approximately 915 m/min (3000 ft/min). The gas flow must be constant with time for steady flow. There must be no cyclonic gas flow in the duct.
   e. If a multipoint calibration is performed, the duct gas velocity should be variable across the range of 180 to 1525 m/min (600 to 5000 ft/min).
5. Support system to ensure that pitot alignment is level and parallel to the duct axis
6. Tubing and quick connection fittings
7. Barometer

Calibration Procedures

The duct gas flow system should be established at a steady flow rate and should be checked to ensure that there is no cyclonic gas flow. The pressure differential gauge should be thoroughly checked for proper zero, level, fluid density, and volume, and it should be set up on an area free of vibration. The pitot tube lines should be arranged so that they may be easily and quickly switched from one pitot tube to another. Always leave manometer connections set and switch lines at the pitot tube.

1. Leak-test the pitot tubes and tubing by sealing the pitot tube impact opening and then establishing a positive pressure at the opening greater than 7.6 cm (3 in.). The manometer pressure should remain stable for at least 15 seconds. Repeat the procedure for the static pressure side of the pitot tube, using negative pressure. Perform this check for all pitot tubes used in the calibration.

2. Using the standard pitot tube, measure the gas velocity pressure at the center of the calibration duct. Simultaneously, measure gas temperature. The sensing orifice must be parallel to the duct axis and perpendicular to the gas flow (Figure 7-12).

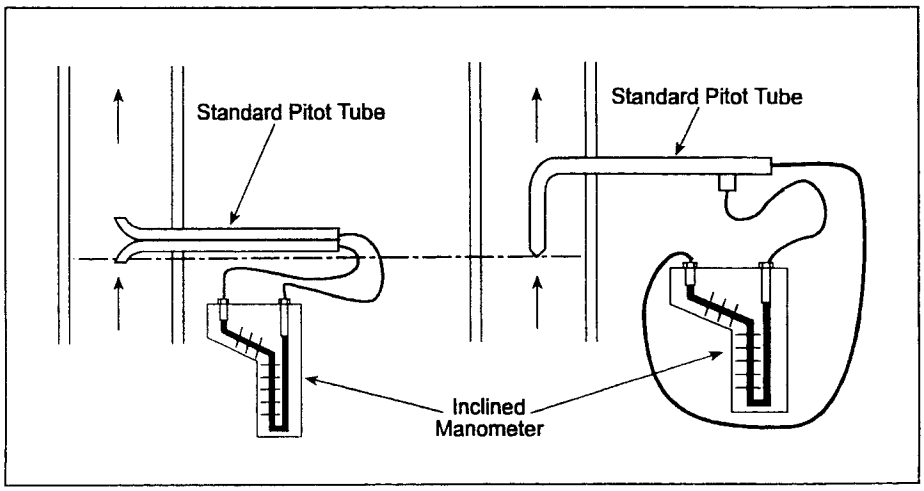

Figure 7-12. Pitot tube position in duct

The standard pitot tube entry port should be sealed around the tube, with no sealing material protruding into the duct, and the Type S pitot tube port should be sealed.

3. Record all data (Figure 7-13), and then disconnect the standard pitot tube from the differential pressure gauge, remove the tube from the duct, and seal the port.

Pitot Tube Calibration

Pitot tube calibration number _____ Date _____

Calibrated by _____

A Side Calibration

Run No.	Δp_{std} cm H_2O (in. H_2O)	Δp_s cm H_2O (in. H_2O)	$C_{p(s)}$	Deviation $C_{p(s)} - \bar{C}_{p(A)}$
1				
2				
3				
		$\bar{C}_{p(side\ A)}$		

B Side Calibration

Run No.	Δp_{std} cm H_2O (in. H_2O)	Δp_s cm H_2O (in. H_2O)	$C_{p(s)}$	Deviation $C_{p(s)} - \bar{C}_{p(B)}$
1				
2				
3				
		$\bar{C}_{p(side\ B)}$		

Figure 7-13. Pitot tube calibration data

4. Assemble the Type S pitot tube and accessories to minimize aerodynamic interferences (Figure 7-14).

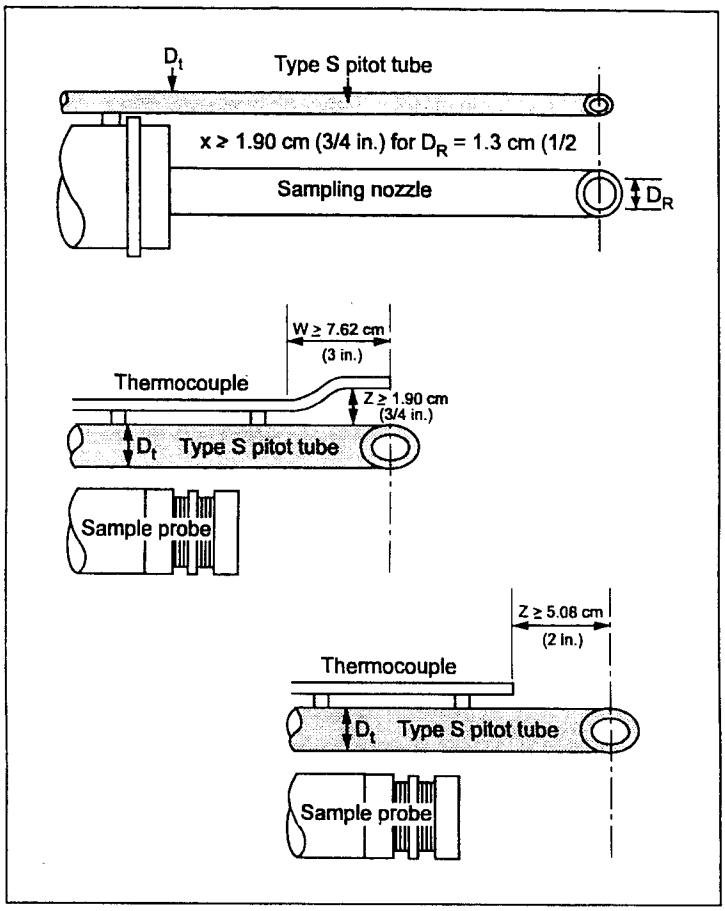

Figure 7-14. Configurations for minimum interference

A very large sampling assembly can disturb the gas flow in small ducts. If the area of the assembled probe-pitot tube is greater than 2% of the duct cross-sectional area, the assembly should be calibrated in a larger test section, or the C_p should be corrected for blockage (see 40 CFR 60.46, paragraphs a-f).

5. Connect the Type S pitot tube to the differential pressure gauge and insert the tube assembly into the duct. The Type S pitot tube must measure the gas velocity pressure at the same point in the duct as the standard pitot tube, and the pitot leg A must be properly aligned to the gas flow (Figure 7-12). Seal the area around the Type S pitot tube, then record all data (Figure 7-13).

6. Repeat the preceding steps until three readings have been made for leg A. Calibrate leg B in the same way. Calculate the pitot tube coefficient by the following equation:

$$C_{p(s)} = C_{p(std)} \sqrt{\frac{\Delta p_{std}}{\Delta p_s}} \qquad (7\text{-}1)$$

Where: $C_{p(s)}$ = Type S pitot tube coefficient
$C_{p(std)}$ = standard pitot tube coefficient
Δp_{std} = velocity head measured by the standard pitot tube, cm H_2O (in. H_2O)
Δp_s = velocity head measured by the Type S pitot tube, cm H_2O (in. H_2O).

The deviation of each $C_{p(s)}$ from the average (C_p) is calculated by $C_{p(s)} - C_{p(\text{leg A or B})}$. Average deviation from the mean for leg A or B is calculated by the following equation:

$$\sigma = \frac{\sum_{n=1}^{3} \left| C_{p(s)} - \bar{C}_{p(\text{A or B})} \right|}{3} \qquad (7\text{-}2)$$

σ must be ≤ 0.01 for the test to be acceptable. $\left| C_{p(\text{side A})} - C_{p(\text{side B})} \right|$ must also be ≤ 0.01 if the average of $C_{p(\text{side A})}$ and $C_{p(\text{side B})}$ is to be used.

Barometer Calibration

The field barometer should be calibrated against a laboratory mercury barometer before each field use. If the field barometer can not be adjusted to read within 5.1 mm (0.2 in.) Hg of the laboratory barometer, it should be repaired or replaced. The field barometer should be well-protected during travel.

Calibration of a Standardized Dry Gas Meter

Reference volume meters are expensive for the average source sampling laboratory. An inexpensive dry gas test meter calibrated against a reference volume meter is accurate and convenient. This standardized test meter may then be used to calibrate sampling console dry gas meters.

Calibration Equipment

1. Spirometer
2. Dry gas test meter (0.1 ft^3 /meter revolution). This must be a test meter to ensure sufficient accuracy
3. Oil manometer (0-2 in. H_2O)

4. Leak-free pump (lubricated fiber vane pump with appropriate oil traps on diaphragm pump with gas pulse compensating baffle)
5. Needle valve
6. Three-way valve
7. Two dial thermometers capable of reading gas temperature ± 2° F

Calibration Procedures

Possible equipment configurations for dry gas meter calibration are shown as Figure 7-15.

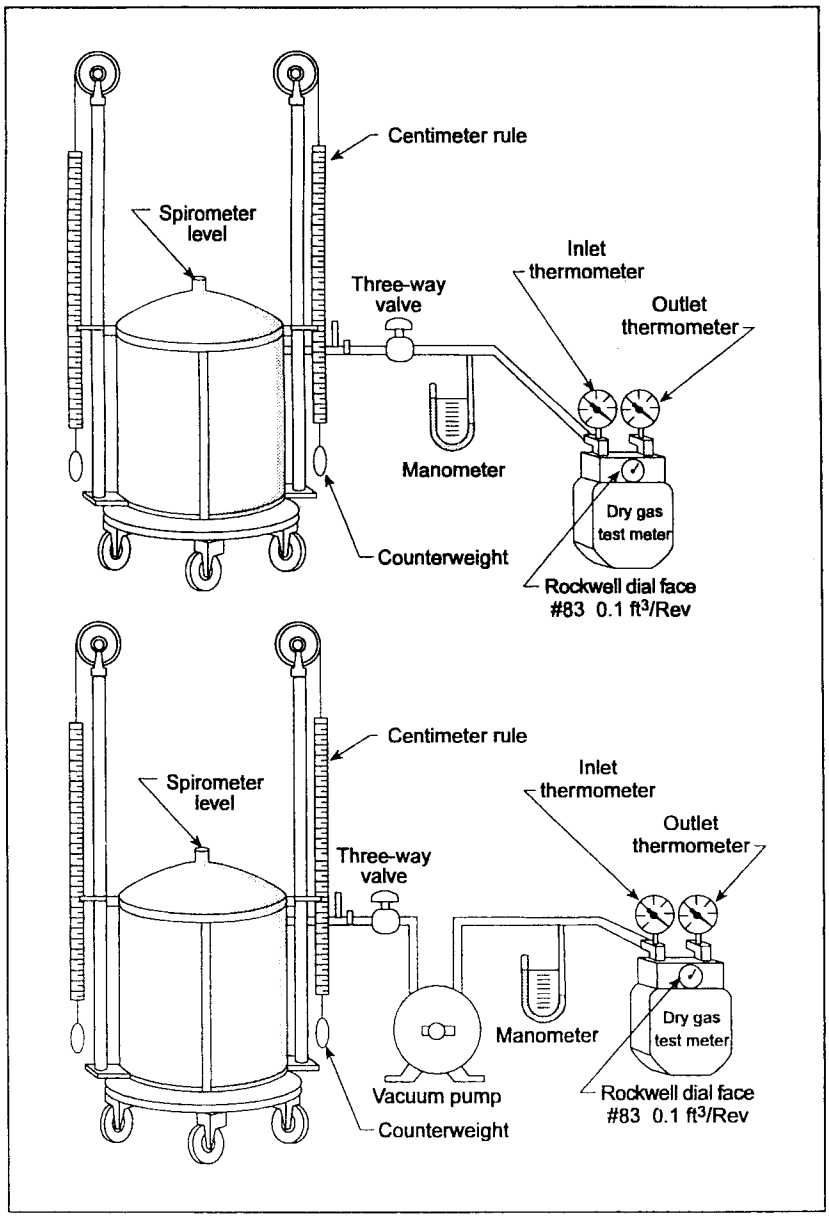

Figure 7-15. Dry gas meter calibration configuration

The meter must be calibrated at several flow rates corresponding to pressure differentials (ΔH) of 0.1, 0.5, 1.0, and 1.5 in. H_2O. The 1.5 ΔH may be achieved by weighting the spirometer bell or using the pump; the other ΔH's can be established without the pump. The pump could increase the gas temperature from the spirometer to the dry gas meter. If it does, gas volume must be corrected for a temperature increase. Calibration of the meter without a pump in the system eliminates the need for temperature corrections.

1. The calibration system should be assembled and thoroughly tested for leaks at ≥ 2 in. H_2O. All leaks should be eliminated.

2. Level the spirometer and fill it with air. Allow the bell several minutes to stabilize.

3. Completely open the spirometer outlet valve and establish a 0.1 in. H_2O manometer reading into the dry gas meter using the gas-flow needle valve. Close the spirometer outlet valve.

4. Read the spirometer meter stick settings. Read the dry gas meter dial value.

5. Open the spirometer outlet valve, check the manometer reading and allow 0.5 ft^3 of air to flow to the dry gas meter (five revolutions of 0.1 ft^3/revolution dry gas meter dial).

6. Stop the airflow. Record the dry gas meter and spirometer settings on the calibration form (Figure 7-16). Repeat the procedure for the other ΔH values. Calculate and average the dry gas meter correction factors. If the factor is outside the tolerance 1 ± 0.02, adjust the dry gas meter internal sliding vanes and recalibrate.

If a pump is used in the calibration apparatus, it could heat the gas entering the dry gas meter. This possibility requires that the dry gas meter volume be corrected to conditions in the spirometer by the equation

$$V_{m\,(corr)} = V_m \left[\frac{T_{amb}\left(P_b + \frac{\Delta H}{13.6} \right)}{P_b T_{m\,(avg)}} \right] \qquad (7\text{-}3)$$

When a pump is used, a three-way valve is employed to establish the flow rate through the dry gas meter, using atmospheric air. The valve is switched to the spirometer, and the dry gas meter is read.

Standardized Dry Gas Meter Calibration

Name _____ Date _____

Ambient Temperature _____ Barometric Pressure _____

Dry Gas Test Meter No. _____ Dry Gas Meter Correction Factor (DGMCF) _____

Spirometer Displacement Factor _____

Manometer	Spirometer Volume (V_{spir})	Dry Gas Meter Volume (V_m)	Dry Gas Meter Correction Factor
0.1 in. H_2O	Final _____ Initial Displacement Volume (V_{spir})	Final _____ Initial _____ Volume (V_m) _____ T_m _____	
0.5 in. H_2O	F I D V_{spir}	F _____ I _____ V_m _____ T_m _____	
1.0 in. H_2O	F I D V_{spir}	F _____ I _____ V_m _____ T_m _____	
1.5 in. H_2O	F I D V_{spir}	F _____ I _____ V_m _____ T_m _____	
			Average DGMCF

Spirometer Volume* (V_{spir})

displacement (cm) × displacement factor (L/cm) = V_{spir} L

Dry Gas Meter Correction Factor (DGMCF)

$$\frac{V_{spir}}{V_m} = \text{DGMCF}$$

Average Dry Gas Test Meter Correction Factor Tolerance SV/DV = 1 ± 0.02

*0.03431 ft^3/L

(L)(.03431 ft^3/L) = ft^3

Figure 7-16. Form for standardized dry gas meter calibration

Calibration of the Source Sampling Nomography

A number of nomographs are available commercially. These instruments are used to solve graphically the sampling nozzle sizing equation.

$$D_n = \sqrt{\frac{0.0358\ Q_m P_m}{T_m C_p (1 - B_{ws})}} \sqrt{\frac{T_s M_s}{P_s \overline{\Delta p}}} \qquad (7\text{-}4)$$

Where:
- D_n = nozzle diameter (in.)
- Q_m = volumetric flow rate through meter (ft^3/min)
- P_m = absolute pressure at meter (in. Hg)
- P_s = absolute pressure at stack (in. Hg)
- T_m = absolute temperature at meter (°R)
- T_s = absolute temperature at stack (°R)
- C_p = pitot tube calibration coefficient
- B_{ws} = water vapor in stack gas, volume fraction
- M_s = molecular weight of stack gas, wet basis (lb/lb-mole)
- $\overline{\Delta p}$ = average velocity head of stack gas (in. H_2O)

and the isokinetic rate equation

$$\Delta H = \left[846.72\ D_n^4 \Delta H_@ C_p^2 (1 - B_{ws})^2 \frac{M_d T_m P_s}{M_s T_s P_m} \right] \Delta p \qquad (7\text{-}5)$$

Today, programmable calculators are often used to solve these equations. Also, a number of plastic slide rules are currently available. These are somewhat more accurate and more convenient to use than the traditional source sampling nomograph.

If a nomograph is used, it should be thoroughly checked for scale accuracy and alignment. Nomograph calibration forms (Figure 7-17) help in making these checks. The traditional source sampling nomograph assumes that the Type S pitot tube has a C_p of 0.84. For C_p values different from 0.84, the C factor obtained on the nomograph must be adjusted by the method given in Form A (Figure 7-17).

The traditional source sampling nomograph also assumes that the molecular weight of the stack gas is 29.1 lb/lb-mole. For molecular weights appreciably different from this value, the C factor of the nomograph should be further adjusted by the method given in Form B (Figure 7-17).

Traditional source sampling nomographs are usually made by fixing a decal on a plastic board. Unfortunately, the scales printed on the decal frequently become misaligned when the decal is applied to the board. Form C (Figure 7-17) gives a procedure that one can use to check the nomograph alignment. The calibration form gives the values used to check

the alignments. The check is accomplished by positioning the marker line through the ΔH and Δp points given, and then tightening the pivot point. The ΔH reading for each Δp value given is then read. If any ΔH readings are off-scale or differ by more than 3% of the proper values, the scale is misaligned. Nomographs that indicate such misalignment should be returned to the manufacturer and replaced.

Form D (Figure 7-17) gives a procedure for checking the accuracy of the nomograph. Here the true values obtained by using the preceding equations are compared to the values obtained by the nomograph manipulations. Calculated and nomograph values should not differ by more than 5%. Nomographs showing greater error should be returned to the manufacturer and replaced.

Source Sampling Nomograph Calibration Data

Form A. Correct the C factor obtained in normal operation of the nomograph for $C_p$observer $\neq 0.84$ by:

$$\text{C factor (Adjusted)} = \text{(C factor nomograph)} \quad \frac{(\text{Pitot tube } C_p)^2}{(0.84)^2}$$

Nomograph ID No.	Nomograph C Factor	Pitot C_p	$\frac{(C_p)^2}{(0.84)^2}$	Adjusted C Factor

Form B. Correct the nomograph C factor for $M_d \neq 29$ lb/lb-mole

$$\text{C factor (adjusted)} = \text{(C factor nomograph)} \quad \frac{1-B_{ws}+18\ B_{ws}/29}{1-B_{ws}+18\ B_{ws}/M_d}$$

Nomograph ID No.	Nomograph C Factor	Stack Gas Dry Molecular Weight (M_d)	Adjusted C Factor

Form C. Scale alignment (check all nomographs)

	Step 1	Step 2	Step 3		
	Set marker on and tighten pivot	Set one end of marker on	ΔH should read	Nomograph ID No._____ actual ΔH reading	Nomograph ID No._____ actual ΔH reading
Alignment Test 1	ΔH = 0.1	Δp = 0.01	1.0		
	Δp = 0.001	Δp = 0.1	10.0		
Alignment Test 2	ΔH = 10.0	Δp = 1.0	1.0		
	Δp = 10.0	Δp = 0.1	0.1		
Alignment Test 3	ΔH = 1.0	Δp = 1.0	10.0		
	Δp = 0.1	Δp = 0.01	0.1		

Form D. Nomograph accuracy*

Meter Console $\Delta H_@$	Meter T_m°F	Stack Gas B_{ws} x 100	P_s	P_m	Stack T_s°F	$\overline{\Delta p}$	Nomo-graph C Factor	Cal. Nozzle D_n	Nomo-graph ΔH	Cal. ΔH
1.84*	70	5	29.92	29.92	1000	1.00				
1.00	140	10	29.92	29.92	300	2.00				
2.00*	100	30	35.9	29.92	500	2.00				

*Assume $Q_m = 0.75$; $C_p = 0.84$; $B_{wm} = 0$; $M_d = 29.0$

Figure 7-17. Forms for source sampling nomograph calibration

Calibration of the Probe Nozzle Diameter

The probe nozzle should be made of 316 stainless steel or quartz with a sharp, tapered leading edge. A taper angle of ≤ 30° on the outside of the sampling nozzle will preserve a constant internal diameter. The nozzle should be a buttonhook or elbow design so that the nozzle opening is below the pitot tube sensing orifice. This is necessary for isokinetic sampling. Alternate construction materials or nozzle shapes must be approved by the administrator.

The sampling nozzle must be calibrated before use in a source experiment. Calibration should be done in the laboratory and checked just prior to use in the field. Inside/outside calipers are used to measure the interior nozzle diameter to the nearest 0.025 mm (0.001 in.).

The calipers are inserted as close to the edge of the nozzle opening as possible; readings are then taken on three separate diameters and recorded. Each reading must agree within 0.1 mm (0.004 in.), or the nozzle must be reshaped. Any nozzle that has been nicked, dented, or corroded must be reshaped and recalibrated. All calibrated nozzles should be permanently identified.

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Chapter 8

Sampling Train Configurations and PM_{10} Sampling Methods

Method 5 is the principal method used for sampling particulate matter from NSPS sources. However, other particulate sampling methods can also be used and may be applied for specific source categories. These methods include the Methods 8 and 17, given in 40 CFR 60 Appendix A and the PM_{10} sampling methods given in 40 CFR 51 Appendix M. Equivalent methods may be used for special purposes, or when emissions from a given facility are not capable of being measured by Method 5. However, their use is generally subject to the approval of the agency administrator.

Basic Sampling Train Configurations of 40 CFR 60

A number of sampling train configurations are used in the reference methods detailed in 40 CFR 60. Since we have already studied Method 5, it is quite easy to note the differences between Method 5 and the other methods. In fact, the Method 5 sampling technique has proven to be the "basic" particulate sampling method, with most other sampling methods being merely variations on the same theme. The placement of a filter, the addition of Tenax adsorbent, and changes in impinger reactants or absorbents are all features that have given rise to a large "bag of tricks" that the source tester can use to sample particulate matter, metals, acid gases, and volatile organic compounds. The volatile organic sampling train (VOST), semi-VOST method, multimetals train, and even the newer PM_{10} methods are derived from the basic concepts of the Method 5 train.

One must be careful when using other train configurations, since the configuration and sampling conditions can affect what is collected. For example, different materials, such as volatile organic compounds, may be present in the stack as vapor, but may condense at the lower temperatures of the sampling train. These so-called "condensibles" may be caught in the impingers, the back half of the Method 5 train. If this impinger catch is added to the filter catch, the total mass of particulate matter collected will of course be higher.

Adding or ignoring the impinger catch has been a significant issue in many regulatory programs. When specifying a sampling method, it is important that the issue be addressed.

To see the effect of sampling train configuration on the particulate catch, consider the following methods.

Method 5

Method 5 is presented schematically in Figure 8-1.

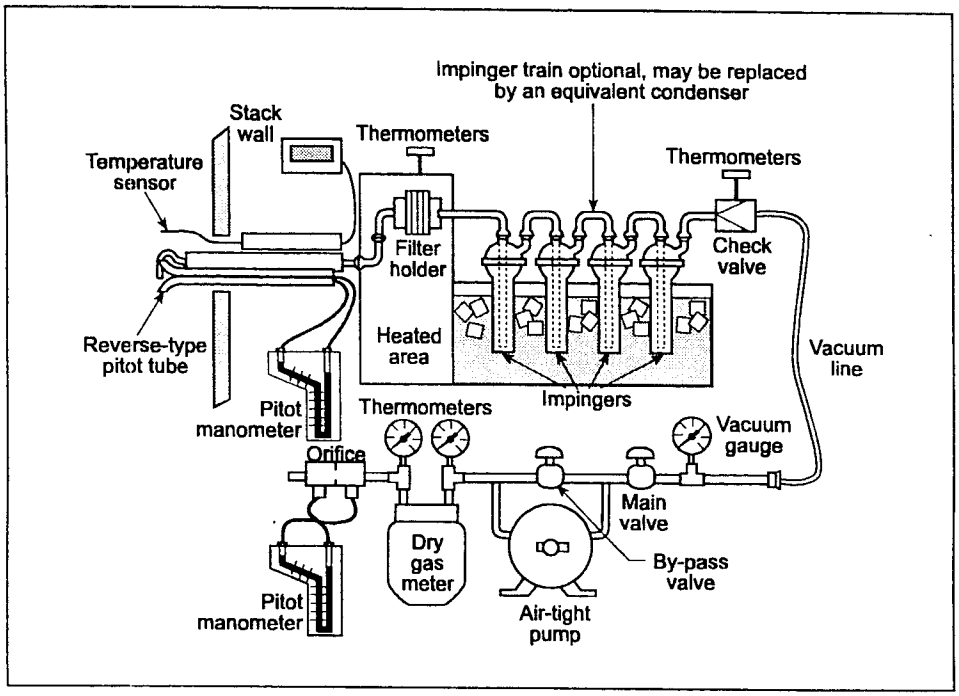

Figure 8-1. Method 5 train configuration

The analytical procedures for the method require the following:

1. Filter glass mat and particulate matter be desiccated to constant weight ± 0.5 mg.
2. Probe, nozzle, and filter holder be washed with acetone.
   a. Acetone blank (100 mL) evaporated at room temperature and pressure.
   b. Acetone and particulate matter evaporated at room temperature and pressure in a tared weighing bottle.
   c. Particulate matter desiccated and weighed to constant weight ± 0.5 mg.
3. Silica gel weighed to nearest gram.
4. Volume of water in condenser measured and recorded. Water discarded.

The sampling train configuration and the analytical procedure outlined constitute a technical definition of "particulate matter." In effect, particulate matter is solid or liquid matter caught on the filter at the specified temperature of the filter box. This temperature is typically 248°F.

Method 17 - The In-Stack Filter

A schematic diagram of the Method 17 in-stack train is illustrated in Figure 8-2.

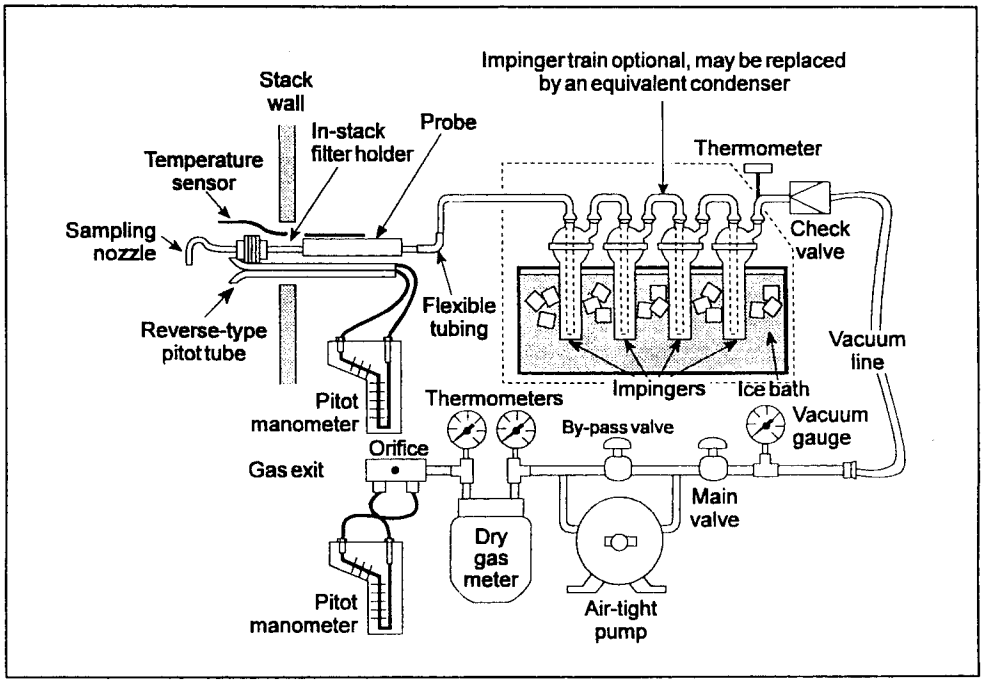

Figure 8-2. Schematic of an in-stack filter system

During Method 17, the filter is maintained at stack temperature and pressure. Typical analytical procedures consider the particulate matter collected on the filter only. This system, therefore, defines only solid or liquid particulate matter collected at stack conditions. Particles penetrating the filter and settling in the probe or impingers are generally ignored.

Gaseous pollutants that condense at temperatures lower than the stack temperature are trapped in the condenser. If the analysis excludes the condenser catch, these materials are not part of the "particulate matter" and the resultant particulate concentration calculated could be lower than that determined by Method 5 (e.g., if the material condensed at 248°F, the Method 5 filter box temperature). The use of this type of system must therefore be carefully evaluated in the context of the test objectives and source operating conditions.

Method 8 (for Sulfuric Acid Aerosol)

The configuration for this modification of Method 5 is illustrated in Figure 8-3.

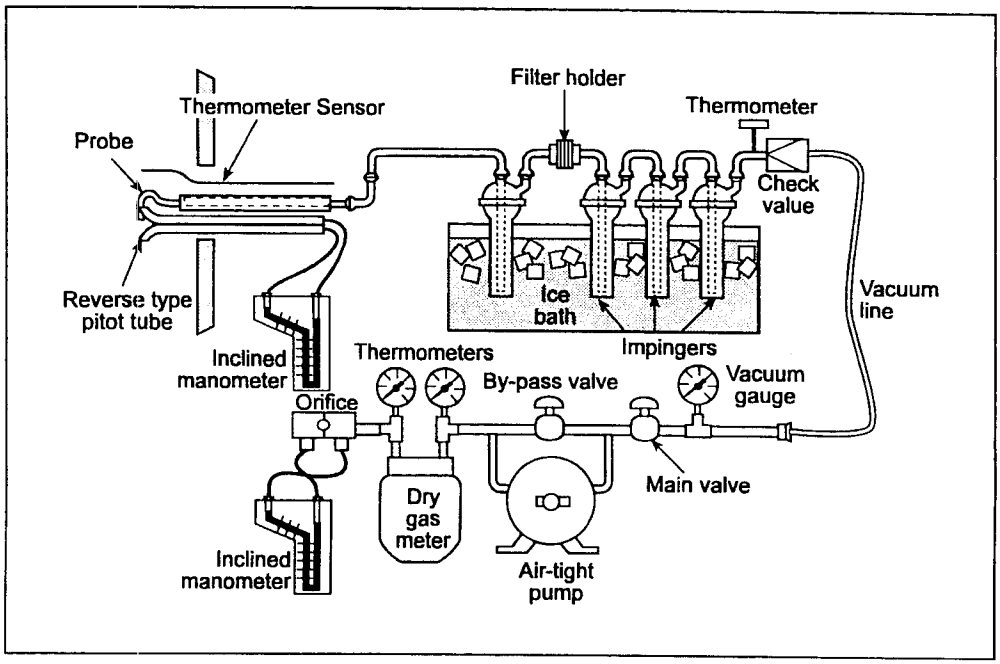

Figure 8-3. Schematic diagram of Method 8

This system uses an out-of-stack filter that collects at ambient temperature and pressure. The filter is located between the first and second condenser. The system traps liquid aerosols and solids on the filters and in the condenser. The particulate matter caught on the filter is trapped at a temperature much lower than the 248 °F recommended for Method 5. Also, the particulate matter found in the first and second condensers might be artifacts of the collection process and not actually be present under stack conditions. Again, application of this method must be evaluated in the context of test objectives and source operations.

Method 13 (for Fluorides)

The modification depicted in Figure 8-4 shows filters located both behind and in front of the condenser.

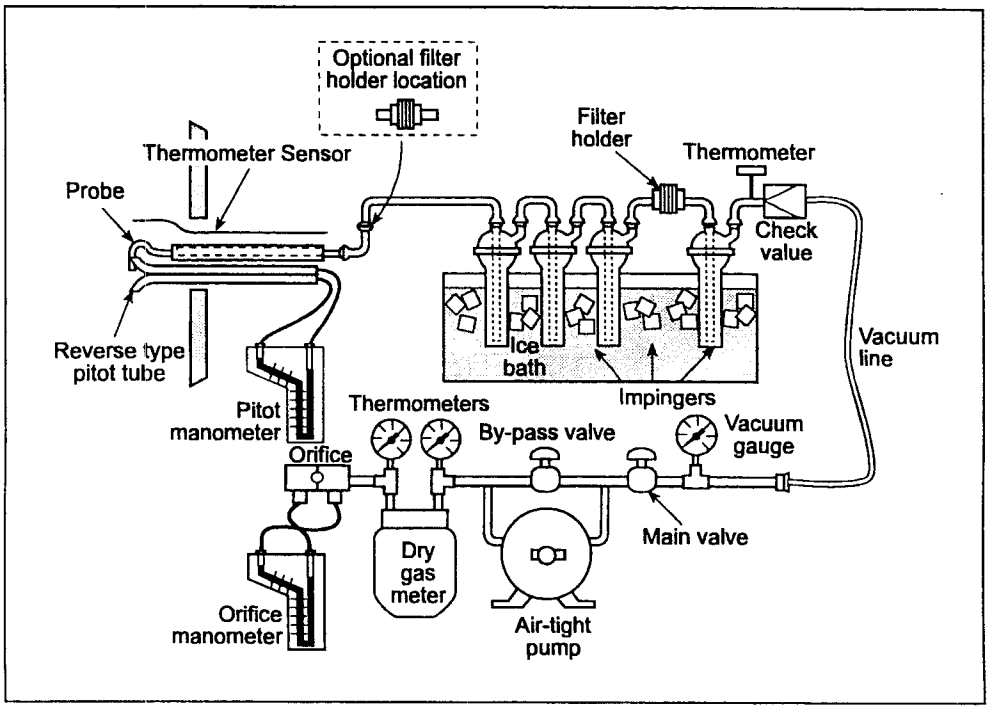

Figure 8-4. Method 5 (Method 13)

The front filter is optional and should be maintained at a temperature of 275°F when collecting fluorides. The second filter temperature is at ambient temperature but may be heated and maintained at a maximum of 248°F. This system can trap particulate matter both on the filters and in the condenser. The selective analysis of various parts of the train is therefore very important. The system can be subject to the biases noted in the other systems; however, it can give a full assessment of the gaseous and particulate fluoride emitted.

Combined Method 5/Method 17 System

Figure 8-5 illustrates a combined system that utilizes both in-stack and external filters.

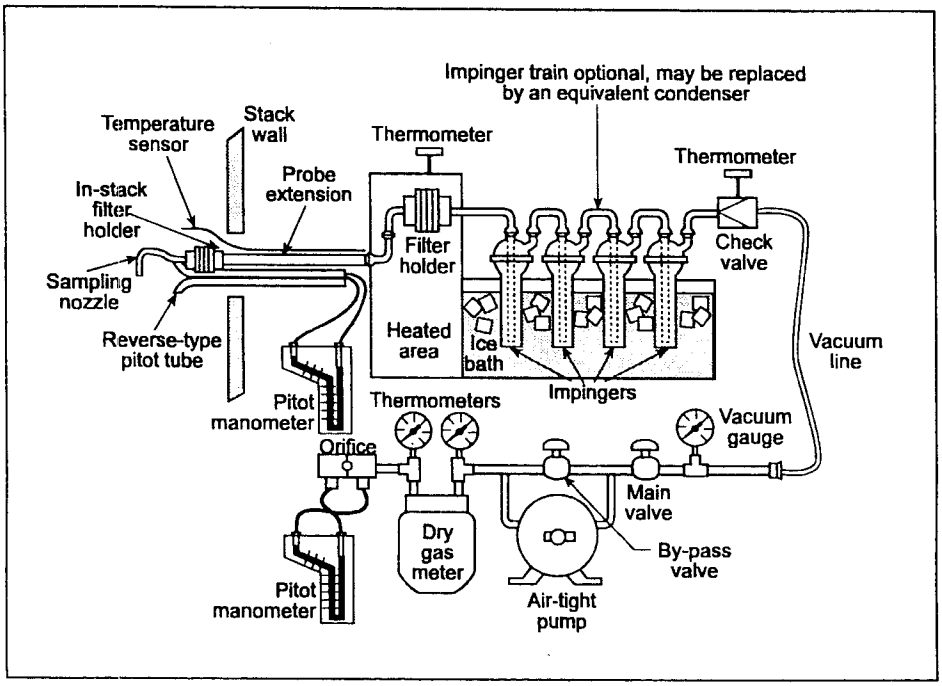

Figure 8-5. A combined system

The in-stack filter in this system collects particulate matter under flue gas conditions, whereas the external filter can be maintained at a temperature suitable for other particulate matter definitions. Depending on the temperatures at which the external filter is maintained, this modification of Method 5 could assess in-stack particulate matter, Method 5 particulate matter, or ambient particulate matter. This system could be a useful research tool.

PM_{10} Methods of 40 CFR 51 Appendix M

Two sampling methods are given in Appendix M of 40 CFR 51 for the collection of particles with sizes less than 10 mm. These so-called PM_{10} methods are available to states that choose to specify methods that address the control of PM_{10} particulate matter only. As we have seen in Chapter 1 of this manual, PM_{10} standards relate to that fraction of particulate matter found in the atmosphere that is most hazardous to human health.

The two methods, Method 201 and Method 201A, use an in-stack sampling cyclone with a cut size, or D_{50}, of 10 μm. That is, the device has a 50% probability that particles larger than 10 μm will escape it. Method 201, the exhaust gas recycle (EGR) method, and Method 201A, the constant rate sampling (CRS) sampling method, are more difficult to perform than Method 5. Only source testers experienced in Method 5 and particle-sizing techniques, should perform these methods.

Method 201 (PM_{10} Exhaust Gas Recycle Method)

In the EGR method, the flue gas is isokinetically extracted from the source into an in-stack cyclone as shown in Figure 8-6. The cyclone separates particulate matter greater than PM_{10} and an in-stack glass fiber filter is used to collect the PM_{10}.

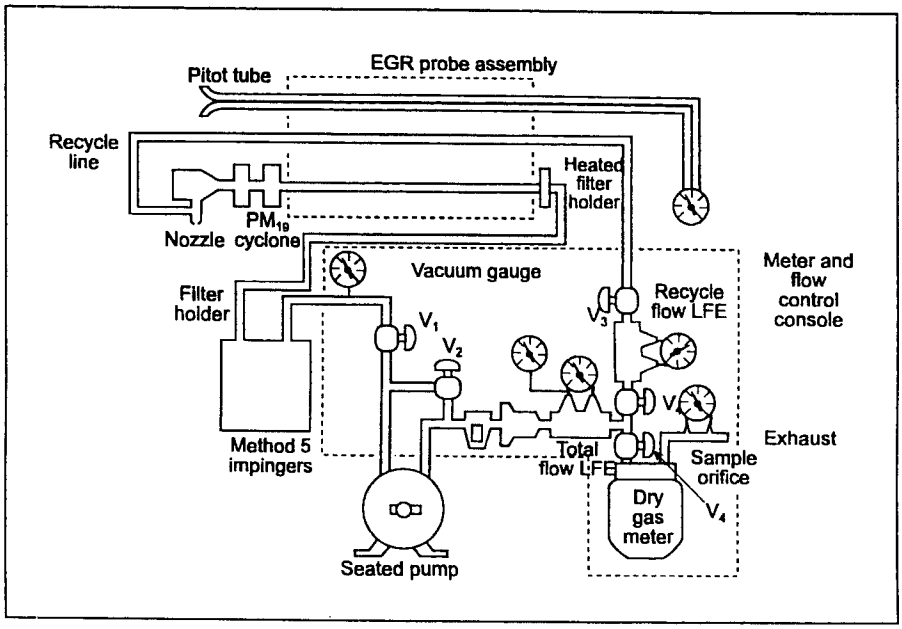

Figure 8-6. The exhaust gas recycle (EGR) method for PM_{10}

The ERG technique utilizes clean, dry gas from the sampling train exit to maintain a constant flow rate through the cyclone since the cut size holds only for a given, constant flow rate. This exhaust gas is recycled into the nozzle. The amount of gas recycled must be calculated and the recycle flow rates must be carefully set.

Method 201A (Constant Sampling Rate Procedure)

The CSR method is somewhat easier to perform than the EGR method, but does require a relatively constant flue gas flow rate. Variations from isokinetic sampling conditions must be maintained within well-defined limits. The sampling train is shown in Figure 8-7.

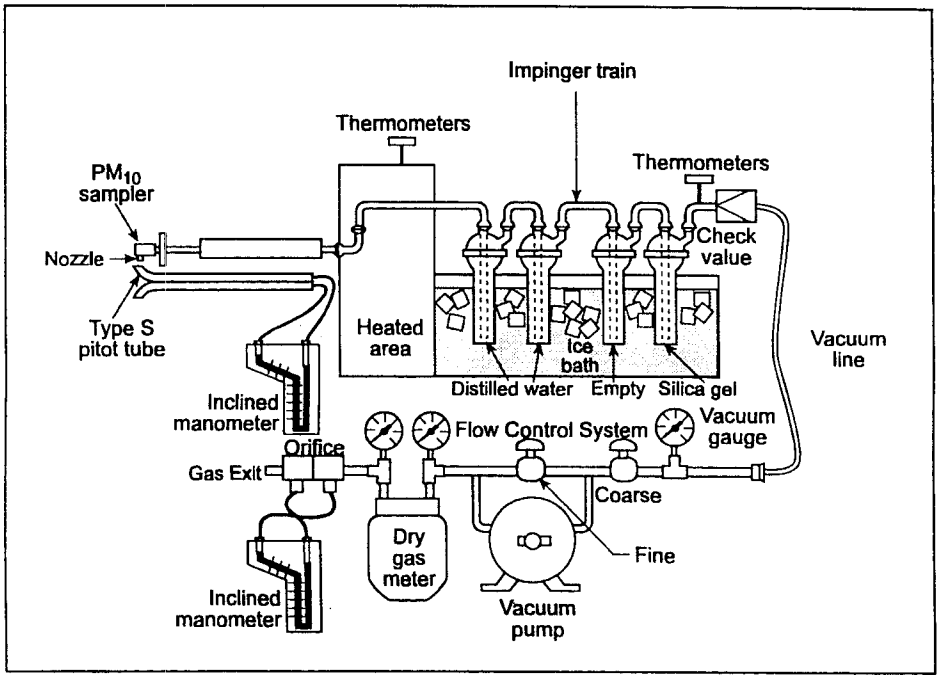

Figure 8-7. The constant sampling rate (CRS) method for PM_{10}

In this method, the flue gas is extracted at a constant flow rate through an in-stack cyclone or impactor. Whichever device is used, the particulate matter greater than PM_{10} is separated from the PM_{10}, and is counted separately. For the method to be acceptable, the flow must be within 100% ± 20% isokinetic.

Due to the expense and inherent difficulties of these methods, they are not always performed. Since Method 5 collects total particulate matter, the Method 5 particulate catch should always be equivalent to the sum of the PM_{10} and cyclone catch of the EGR or CSR methods. If a PM_{10} standard can be met with Method 5, then it should be able to be met using a PM_{10} method. In practice, the easy way out is to do Method 5 and hope for the best.

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Chapter 9

Particle Sizing

In the field of air pollution measurement and control, particles are characterized by their physical, optical, and chemical properties. In Method 5, we are primarily concerned with the size and mass of the particles. The size is important in our isokinetic sampling considerations and the mass of particles collected relates to the reported results of Method 5—particulate mass concentration. The optical properties of a particle are also related to the particle size and are important when considering issues of opacity. The chemical and toxic properties of a particle are important also. However, as we have seen in Chapter 1, the size of a particle will determine whether or not it will remain in the human pulmonary system and cause damage. The primary distinguishing physical feature of any particle is, therefore, the particle size.

In terms of both emission standards (e.g., the PM_{10} standards) and the dependence of pollution control equipment efficiency on particle size, a knowledge of flue gas particle size distributions has become increasingly important.

Particle Size

A particle's size is usually expressed in terms of a diameter. The most widely used unit describing particle diameter is the micron.

$$1 \text{ micron } (\mu m) = 0.001 \text{ mm} = 10^{-4} \text{ cm} = 10^{-6} \text{ m}$$

It is commonly assumed that particles in flue gases are spherical and that the particle diameter represents the diameter of a sphere. However, except for liquid droplets and metallurgical fumes, particles may be nonspherical. To deal with such particles, it becomes necessary to define an "equivalent diameter" that depends upon the geometric or aerodynamic properties of the particle.

The **aerodynamic diameter** is defined as the diameter of a sphere of unit density, having the same falling speed in air as the particle (Figure 9-1). The aerodynamic diameter is a function of the physical size, shape, and density of the particle. It is useful in designing air pollution control devices and is usually measured by using an inertial "impactor."

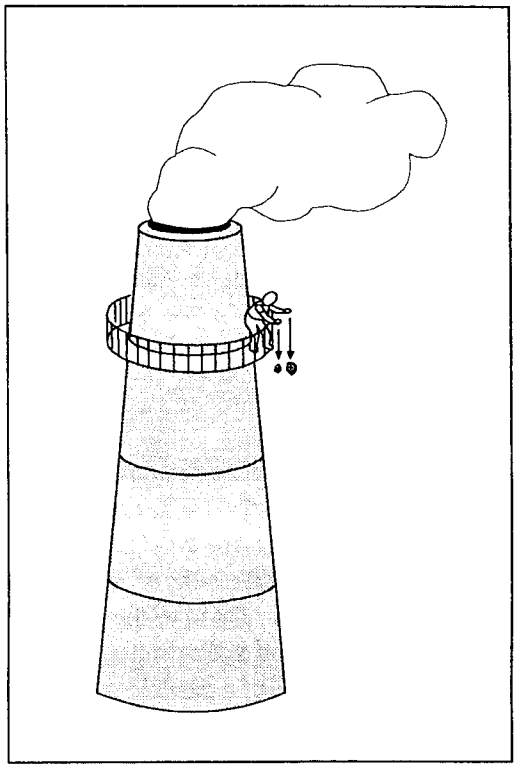

Figure 9-1. Aerodynamic diameter

Inertial Particle Sizing

An inertial impactor is the most frequently used device for flue gas particle size determinations. The impactor measures the distribution of different particle sizes in the flue gas. In practice, the impactor is attached to the end of a sample probe to collect particles on a number of in-stack filters.

The operating principle of an impactor is illustrated in Figure 9-2.

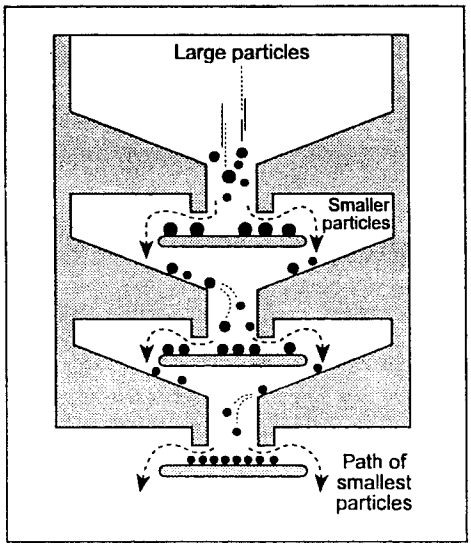

Figure 9-2. Operation of an inertial impactor

The device is constructed using a succession of stages. A stage consists of an orifice plate containing a pattern of small orifice openings. In each stage, the gas stream passes through the orifice opening and forms a jet that is directed toward an impaction plate. The larger particles will impact on the plate if their momentum is large enough to overcome the drag of the gas stream as it moves around the plate. The orifice openings in each successive plate are smaller than those in the preceding stage. The velocity of the gas stream and the particles in the stream increase as the stream advances through the impactor. Eventually, the smaller particles acquire enough momentum to break through the gas streamlines to impact on a plate. Each plate collects particles over a size range determined by the orifice size and gas stream velocity. The smallest particles are caught on a back-up filter.

Typical cascade impactors consist of a series of stacked stages and collection surfaces. Depending on the calibration requirements, each stage contains from one to as many as 400 precisely drilled jet orifices, identical in diameter in each stage, but decreasing in diameter in each succeeding stage (Figure 9-3).

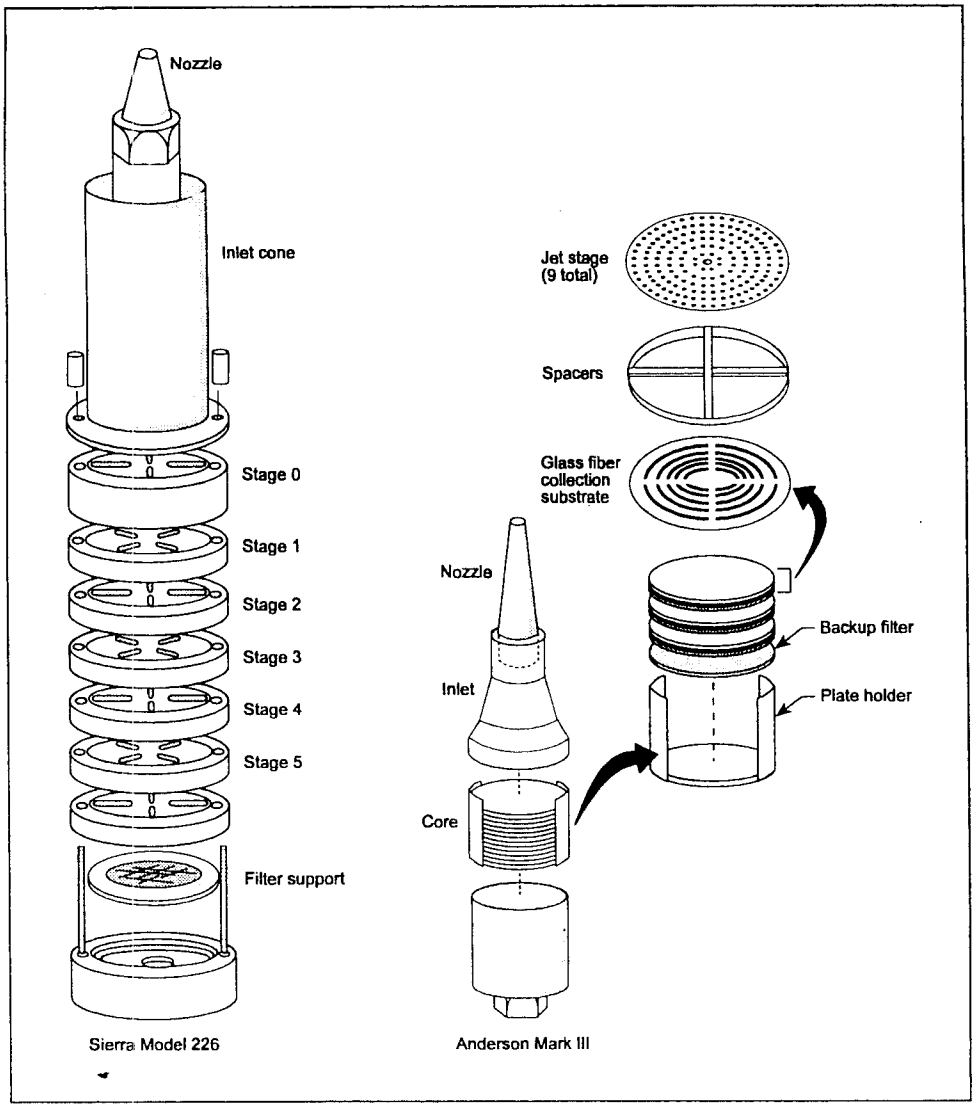

Figure 9-3. Two types of commercial cascade impactors

Particles are collected on pre-weighed, individual stages—usually filters made of glass fiber or thin metal foil. Adhesive, electrostatic, and Van der Waals forces hold the particles to the collection surfaces and to each other. The particles are not blown off the collecting plates by the jets of gas because these jets follow laminar flow paths. Because there are no turbulent areas, a dead air space results over and around the samples. Particles that bounce or are otherwise difficult to collect may require the addition of grease to the collection filter so that the particles will "stick."

Once the sampling is completed, the collection filters are weighed. A particle size distribution is obtained by calculating the relative mass of particulate matter collected on each stage.

The effective range for measuring the aerodynamic diameter using an impactor is generally between 0.3 and 20 μm. Some vendors have claimed size fractionation as small as 0.02 μm with the use of 20 or more stages.

Impactors are one of the most useful devices for determining particle size because of their compact arrangement and their ability to draw a sample directly from the flue gas. This in-situ device is generally not subject to biases created by electrostatic and thermal gradients, particle agglomeration in the sample probe, or new particle formation at lower than stack temperature. Also, the particle fractionation occurring in the impactor is based on the particle aerodynamic diameter. The resultant particle size distribution is therefore directly relevant to particle behavior in air pollution control equipment.

The particle size for a given stage is a "fractionation size," corresponding to size cutoff with a percentage of different size particles above or below this size cutoff. The D_{50} for any stage is defined as the size of particles collected on each stage having at least a 50% collection efficiency for a given set of impactor conditions. A D_{50} for a collection stage can be maintained only if the particle-sizing device is operated at a gas flow rate that does not cause fracturing or scouring of particles. If the sample gas flow rate is too high, particles can be broken upon impact with the collection stage, or settled particles could be re-entrained into the gas stream. This would create significant errors in collection efficiency.

Other problems, such as particle bounce, overloading, and deposition of particles on the impactor walls, and the diffusion of smaller particles between stages, can cause errors in the sizing measurements. The use of a cascade impactor requires both the application of careful technique and a knowledge of the particle characteristics. The source tester performing this method should be trained and familiar with the considerable body of technical literature that addresses its application and limits.

The Bahco Particle Classifier

The Bahco particle classifier is used to determine particle size from bulk samples. To use this equipment, one must first obtain a relatively large sample on the order of 5 g. The instrument can classify particles over the range of 1 to 60 μm. It is still used today, but its inability to measure in the submicron region is giving way to more recently developed techniques.

To use the classifier, sufficient sample must first be collected using a Method 5 train (or a bulk sample collected by other means can be used). The particulate matter is then taken to the laboratory and run through the classifier (Figure 9-4).

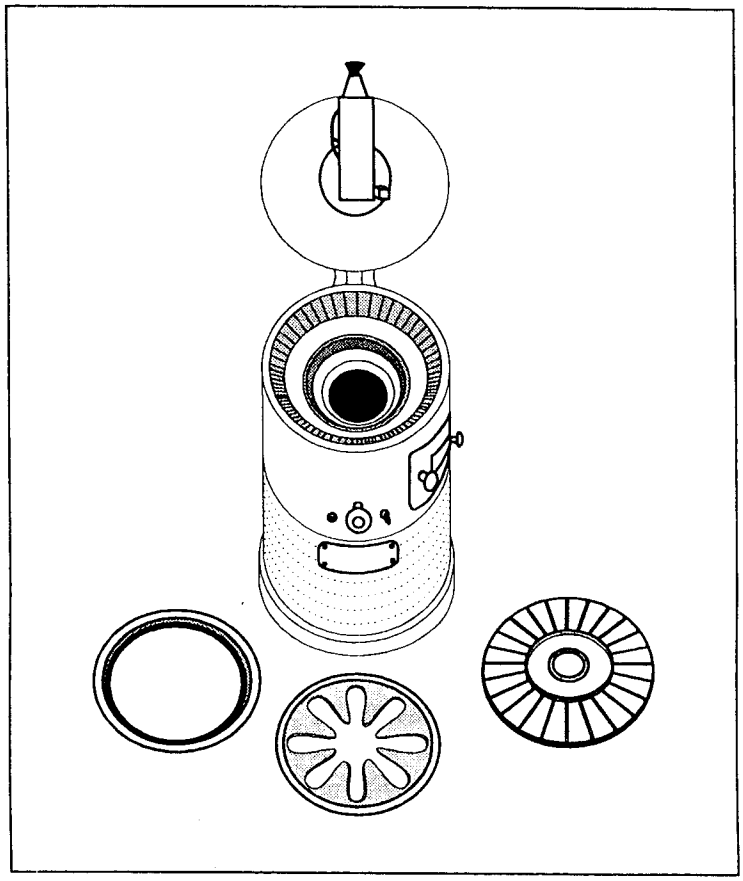

Figure 9-4. The Bahco particle classifier

Electrical Mobility Analyzers

Measurements of particle size distributions can also be made by taking advantage of the electrical properties of the particles. If a particle is electrically charged, either by natural processes or by the addition of a charge by some device, its time of flight will be influenced by an electric field. The particle's time of flight in an electric field is known as **drift velocity** and the ratio of the drift velocity to the electric field strength is known as its **electrical mobility**:

$$\mu_\varepsilon = \frac{v_d}{\varepsilon} \qquad (9\text{-}1)$$

Where: v_d = drift velocity (cm/sec)
ε = electric field strength (volt/cm)
μ_E = electrical mobility (cm^2/volt-sec)

For singly charged particles, the electrical mobility decreases as the particle size increases.

In concept then, an electrical mobility analyzer can be constructed by first charging the particles to be analyzed, injecting them into an electric field and measuring their time of flight (Figure 9-5).

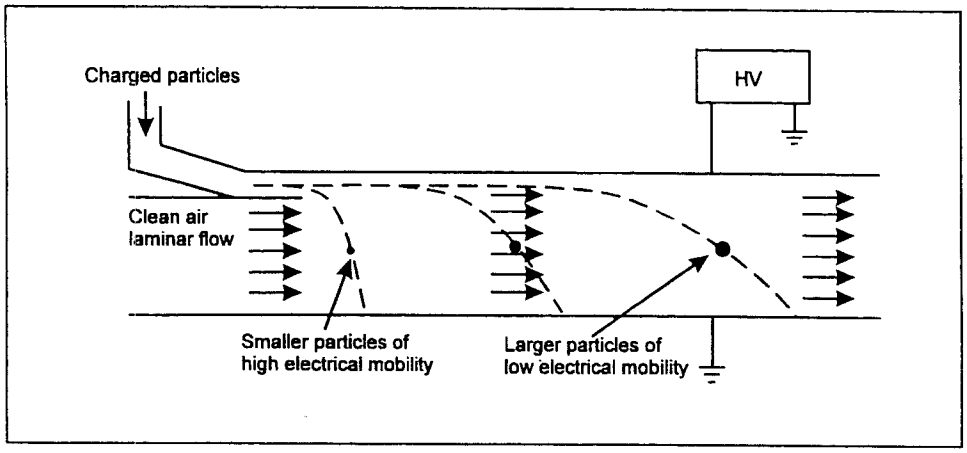

Figure 9-5. Principle of electrical mobility analyzers

In , a parallel plate electrical mobility spectrometer (Figure 9-5), the particles are charged and injected between the plates. A uniform electric field, ε, is placed across the plates, transverse to the motion of the particles. The particle mobility is then determined by detecting where a given size particle settles on the grounded, bottom plate.

Several different types of electrical mobility analyzers have been developed for ambient and source particle sizing studies. The electrical aerosol analyzer (EAA) has been used in source measurements, however; the sample extracted from the stack must first be diluted to a concentration within 1 to 1000 $\mu g/m^3$.

Electrical mobility analyzers measure submicron particles (from 0.003 to 1 μm) well. However, larger particles must first be removed. Problems also occur in charging the particles to a known value and calibration tables are necessary. These tables have been developed for spherical particles, and have limited use when irregularly shaped particles, such as fibers, are to be analyzed.

Other Techniques

A number of other techniques have been used for particle-sizing measurements (Willeke, 1993). However, many of the methods are only feasible for the analysis of particulate matter in ambient air. Other methods, promising for source measurements, have not been commercially developed. Optical methods, such as those based on the phenomenon of Mie scattering (see Chapter 10), and multi-wavelength transmissometry have been widely studied and show promise for the in-situ measurement of particle size. However, such instruments are expensive and the analysis complicated. At present there exists no great commercial need for particle size measurement that the cascade impactor cannot fulfill. Consequently, most of the advanced work in this area is performed in university and government research laboratories.

Data Analysis

A variety of methods exist for presenting particle size data, the most common being the use of frequency or cumulative frequency distribution curves.

A **frequency distribution curve** plots the weight of the particles in a given, incremental size range, against the average particle size of that range (Figure 9-6a).

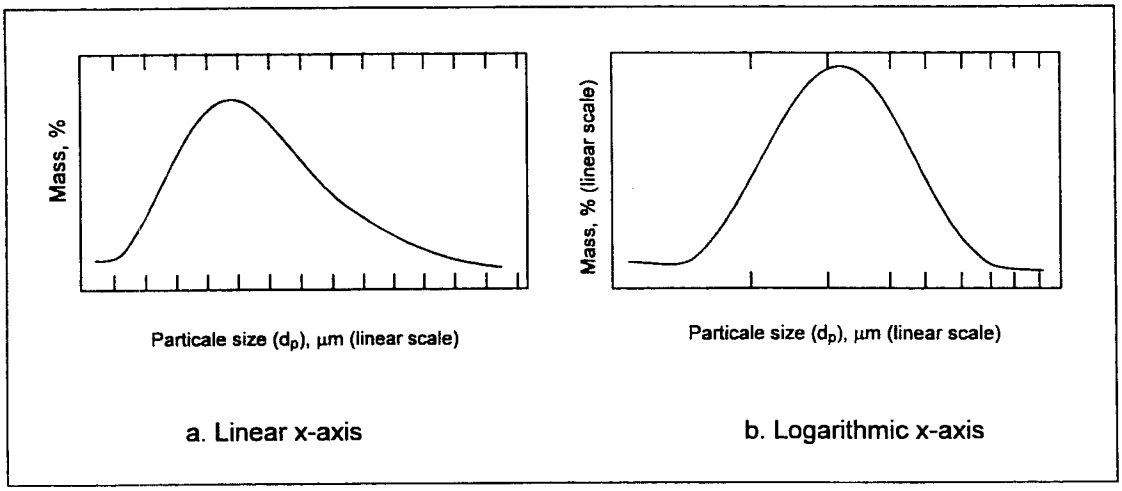

Figure 9-6. Typical log-normal frequency distribution curves for flue gas particles

Most flue gas particle distributions do not follow a simple bell-shaped, normal probability curve. Instead, they are quite often "log-normally" distributed, as shown in Figure 9-6a. If the particle size is plotted on a logarithmic scale (the x-axis) for such distributions, the resultant curve will appear as a typical bell-shaped probability curve (Figure 9-6b).

The **cumulative frequency distribution** (Figure 9-7) is a plot of the fraction of the total weight of particles that have a diameter less than a given size, plotted against that size.

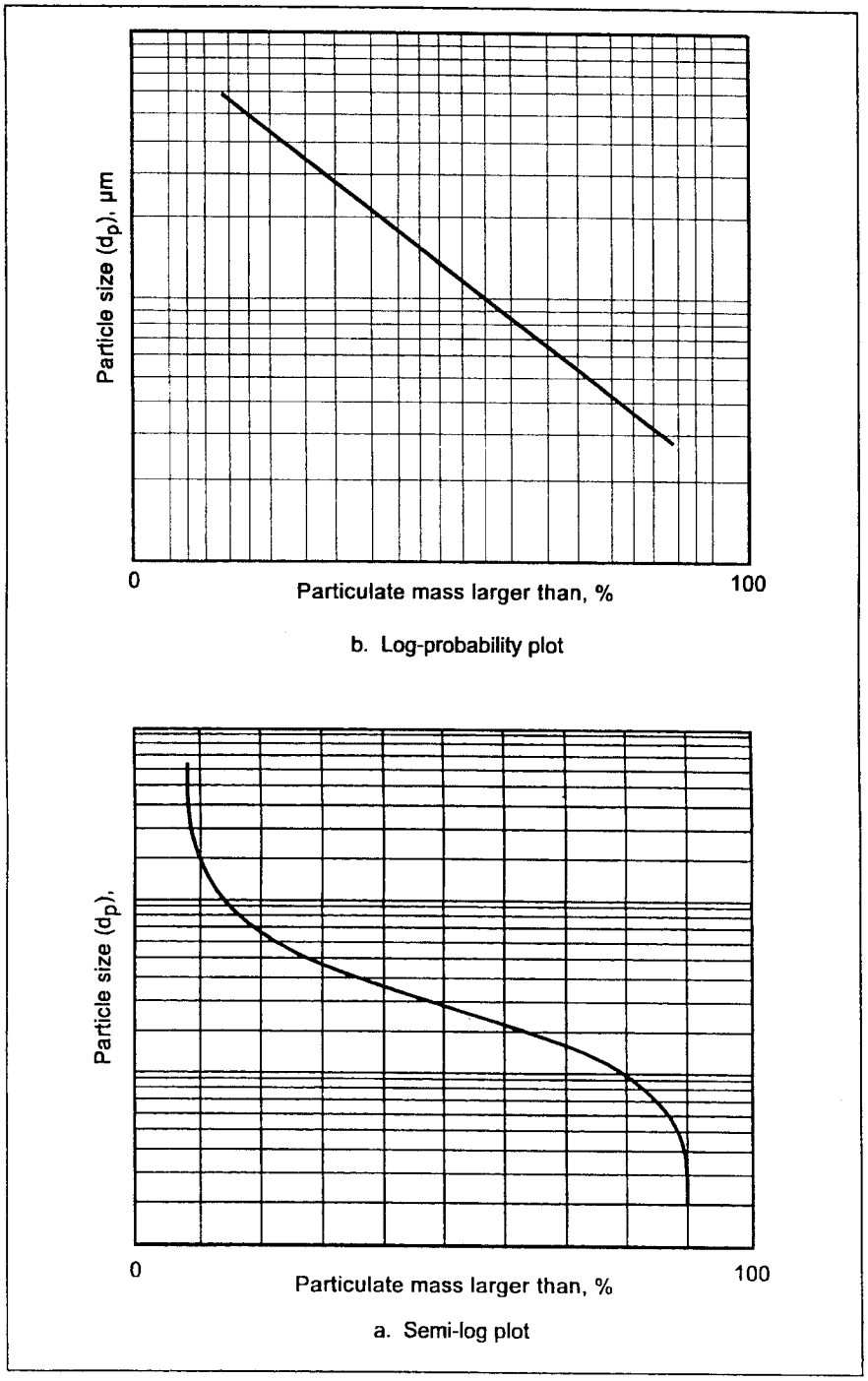

Figure 9-7. Cumulative frequency distribution curve

In a cumulative plot, the weight of the particles collected on each stage is presented as a percent of the total particulate catch. The data is then plotted as percent versus particle diameter. Figure 9-7a shows a plot for a typical log-normal distribution. For a log-probability plot of such a distribution (Figure 9-7b), the resultant curve is linear—a graphical device that greatly aids in data analysis.

The majority of inertial impactor particle size data reduces to the use of D_{50} data. The particles on a given stage are assumed to have a diameter equal to the calculated D_{50} for that stage. Once the D_{50} for each stage has been determined, the weight data can be used to develop a cumulative plot of the particle size distribution.

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Chapter 10

Continuous Particulate Emissions Monitoring

In the preceding chapters, we have discussed manual reference methods. Although these methods can be used to provide valuable source information, the data obtained may not be necessarily representative of day-to-day operating conditions. Due to the planning and preparations necessary for the manual methods, the source is usually notified prior to the actual testing. This lead time allows the source to optimize both operations and control equipment performance in order to pass the tests. Consequently, the tests may not be truly representative of actual source performance.

As a result of this problem, since 1971, the U.S. EPA has, promulgated numerous continuous emission monitoring (CEM) requirements for stationary sources (Jahnke, 1993). These requirements have focused primarily on the continuous measurement of gases such as sulfur dioxide and nitric oxides, and flue gas opacity. Currently, there are no federal requirements for the continuous measurement of particulate mass. A few states have required continuous mass measurement systems through operating permits or through negotiating agreements; however, these applications have not been extensive. Continuous mass measurement requirements are more common in Europe, particularly in Germany where both the regulatory and technical sophistication of continuous mass measurement has become quite advanced.

The problem with continuous mass monitoring is that a method does not exist that can measure mass both directly and continuously. An opacity monitor measures the ability of a flue gas to transmit light. A light-scattering instrument measures the light intensity scattered back from flue gas particles. A beta gauge measures the transmission of electrons through a spot of collected particulate matter. All of these commercially available continuous mass monitoring instruments produce an instrument output that is something other than "grams per cubic meter." This output, however, can be correlated to the particulate concentration.

To continuously measure particulate mass, one first chooses an instrument that measures some property of the particles in the flue gas. The instrument readings are correlated with manual particulate source test method data from Method 5 or Method 17. Source and control equipment operating conditions are varied in order to obtain a range of particulate concentrations. A graph, or correlation, is then made between the instrument response and the manually determined particulate concentrations.

In this chapter, we will discuss commercially available techniques currently used to measure flue gas particulate parameters. We will also discuss the most generally accepted correlation method, the International Standards Organization (ISO) continuous mass measurement standard, ISO 10155.

Measurement Techniques

Measurement techniques used in continuous particulate monitor systems are given in Table 10-1.

Table 10-1. Automated Measurement Methods for Particulate Matter

Optical
Light Attenuation (Opacity Monitors)
Light Scattering
Nuclear
Beta Ray Attenuation
Electrical
Contact Charge Transfer
Electromechanical (Loaded Oscillator)
Piezoelectricity
Cantilevered Beam

Of the methods listed in Table 10-1, the light attenuation technique (using opacity monitors) has been the most extensively studied. Opacity-mass correlation methods are routinely used in Germany and occasionally in the United States. The light-scattering and beta gauge techniques are increasingly being applied due to the good correlations that can be obtained.

Optical - Light Attenuation (Opacity Monitors)

In an opacity monitor, the light attenuation or transmittance through the flue gas is determined by passing a light beam through the stack. The intensity of the light returning, I, is compared with a previously determined reference signal, I_o, to give the transmittance $T = I/I_o$. Because the transmittance of the light beam is the parameter that is actually measured, the opacity monitor is often called a **transmissometer**. Transmittance and opacity are related by the expression:

$$T = 1.0 - Op \qquad (10\text{-}1)$$

Where: T = the fractional transmittance
Op = the fractional opacity

A transmissometer may be constructed in two ways, using either a single-pass system or a double-pass system. In a single-pass system, the light crosses the stack directly to a detector. In a double-pass system (Figure 10-1), the light crosses the stack twice.

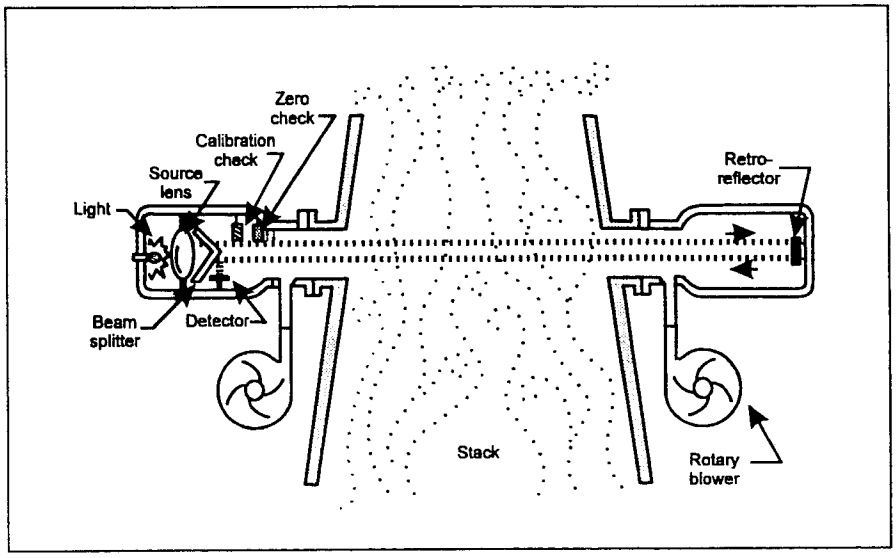

Figure 10-1. A double-pass transmissometer

In the double-pass system shown in Figure 10-1, the transceiver assembly on the left houses both the light source and light detector. By reflecting the projected light from a mirror on the opposite side of the stack, systems can be easily designed to check all of the electronic circuitry, including the lamp and photodetector, as part of the operating procedure. Most transmissometer systems include some type of air-purging system or blower to keep the optical windows clean.

The way in which a transmissometer is used can affect its design. If the instrument data are intended to be correlated with visible emissions data obtained by applying Method 9, the monitor must meet the EPA design specifications given in Performance Specification 1 of 40 CFR 60 Appendix B. This specification requires that the projected light be in the visible region of the electromagnetic spectrum (to compare with observations made by the human eye) and that certain criteria for such things as projection angle, view angle, calibration error, and response time be met. In addition, the monitor must pass a performance test after it is installed in order to determine its drift limits.

If data are to be correlated with particulate mass rate, red or infrared light may be more appropriate. The smaller particles (<5 μm in diameter) contribute greatly to the opacity but not to the particulate mass loading of the flue gas. Red light is not as sensitive to small particles as it is to larger particles, and thus gives a better correlation to particulate mass.

Opacity-mass correlations have been successfully developed for many types of emission sources. However as implied above, correlations may be somewhat sensitive to changes in the particle-size distribution in the flue gas. The conditions for applicability are specified in the ISO 10155 correlation method, which we will discuss later.

Optical - Light Scattering

When light is directed toward a particle, the particle may both absorb and scatter the light. If the wavelength of the light is approximately the same as the radius of the particle, a type of scattering, called **Mie scattering** will occur (originally described by Gustav Mie in 1908). This form of scattering is shown in Figure 10-2.

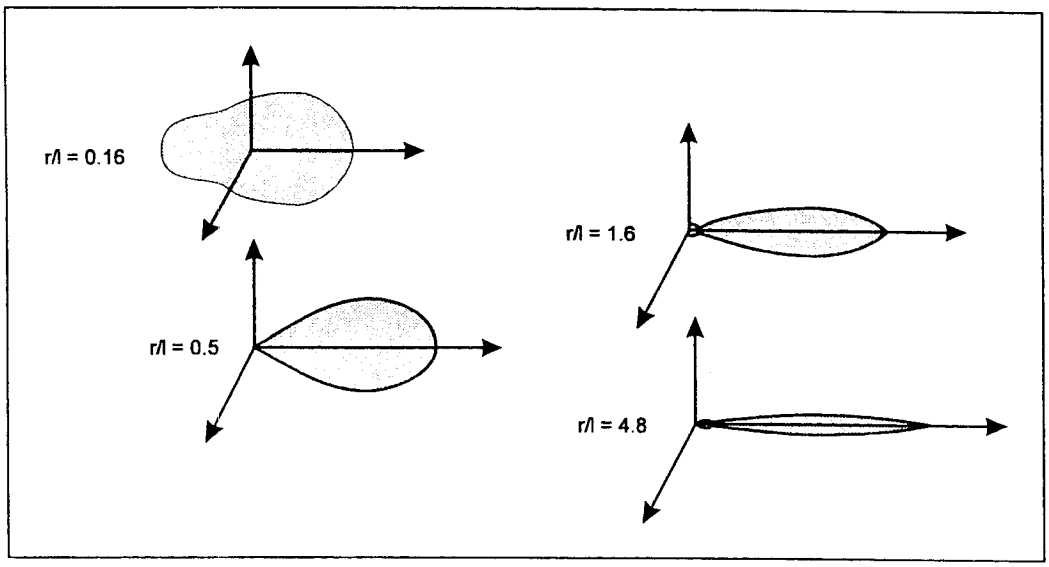

Figure 10-2. Angular dependence of the intensity of light scattered by a spherical particle of index of refraction 1.20. The intensity is arbitrarily normalized in each case. (Source: Ashley, L.E., 1958)

Note from the figure that for values of $r/\lambda < 1.0$ (where r is the particle radius and λ the wavelength of the light), the particle will scatter the light in many directions—forward, backwards, up, down, and so on. For values of $r/\lambda > 1.0$, the scattering will principally be in the forward direction.

Baghouses and electrostatic precipitators used to control the emission of particulate matter will effectively collect particles that are greater than 1 μm (1000 nm) in diameter. It is more difficult, however, to collect particles in the submicron range (<1 μm). These are the particles that will have a higher probability of escaping into the atmosphere. Visible light (range 400 nm to 700 nm) scattering from these particles is, therefore, within the region of applicability of Mie theory for visible and infrared light.

Analyzers have been developed to take advantage of scattering effects. They can be designed to measure either back-scattered light, forward-scattered light, or light scattered at a specified angle. Figure 10-3 illustrates a back-scattering instrument.

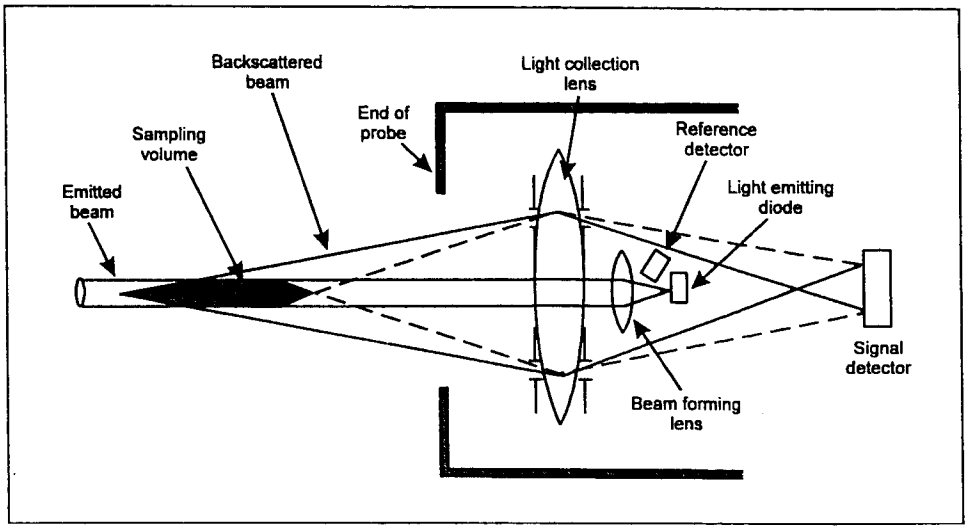

Figure 10-3. A back-scattering continuous mass emission monitor

In this instrument, the light is focused on a sampling volume where the particulate matter in that volume scatters the light. The back-scattered light is in turn focused on the signal detector. A reference detector is positioned next to the light source to monitor the lamp intensity. Figure 10-4 illustrates a side-scattering instrument.

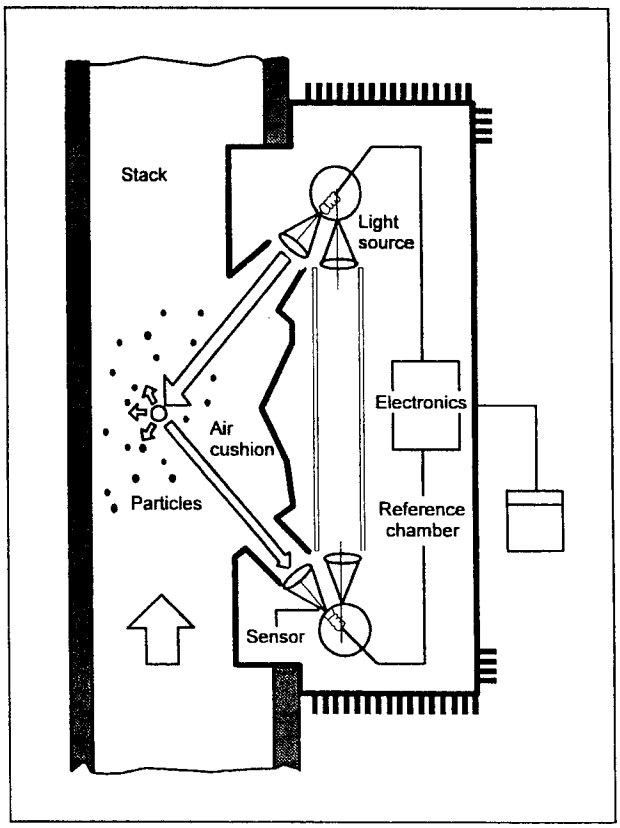

Figure 10-4. A side-scattering continuous mass emission monitor

In this side-scattering device, infrared light is again focused on a sample volume. Instead of measuring the back-scattered radiation, the device locates a detector beneath the lamp such that side-scattered light is detected. A reference measurement is made by monitoring the lamp intensity through a tube passing from the lamp to the detector.

The response of such instruments tends to be linear with respect to particulate concentration; however, manual particulate measurements are still necessary to correlate the response to mass concentrations. The technique is capable of monitoring emission concentrations as low as 0.4 mg/m^3.

Nuclear - Beta Ray Attenuation

When beta rays pass through a material, they can be absorbed or reflected by that material. The transmission of the beta rays is therefore attenuated and the reduction in beam intensity can be correlated to the amount of material present. By using a radioisotope for the beta source (e.g. Kr^{85}, C^{14}), **beta gauges** have been developed that can continuously monitor particulate mass (LBL, 1972) (Figure 10-5).

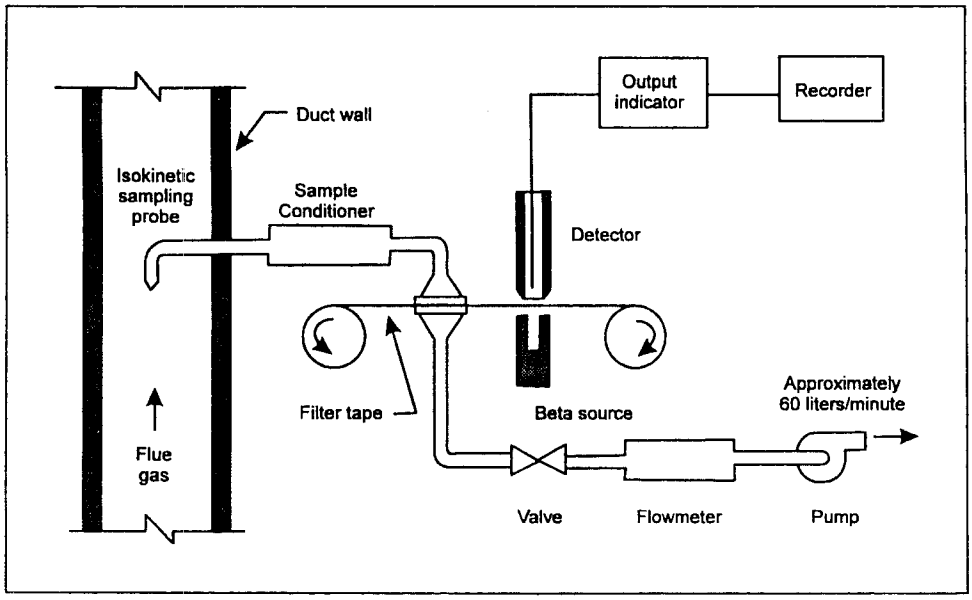

Figure 10-5. A typical beta gauge paper tape monitor

In this device, the flue gas is first drawn isokinetically through a probe. It is then diluted in order to reduce the dew point to levels where condensation of flue gas moisture will not occur in the instrument. The gas is then filtered through a glass fiber filter to produce a spot of collected particulate matter. This spot is then moved between the beta source and detector for a determination of the beta ray attenuation. In practice, a moving filter tape allows the collection and measurement of one data point every 15- to 30-minute period to produce a semi-continuous measurement.

The reduction of the beta ray beam intensity through the spot depends upon the electron density of the collected material and the amount of material present. To produce consistent measurements, there must be a constant relationship between the number of electrons per molecule and the molecular weight. This ratio is essentially the same for most particulate

matter found in coal and oil combustion sources. In principle, the method therefore allows a direct measure of particulate mass without necessarily requiring correlation with Method 5 data. In this method, the sample gas volume is also measured to provide a value for the particulate matter concentration.

The method does however require that the sample be collected isokinetically. Problems may occur with particulate deposition in the sample probe and sampling lines. Spot collection efficiency, particle composition, and gas volumes and dilution ratios are all factors that may produce error. It is therefore still advisable to check or correlate the beta gauge with corresponding Method 5 measurements.

Electrical - Contact Charge Transfer

When two materials having different work functions make contact, there will be a net transfer of electrons from one material to the other after they are separated. This is not an effect based on the accumulation or transfer of static charges, but an effect based upon the intrinsic electronic properties of the materials themselves. The amount of charge transferred depends on other factors besides the differences in work function. These include the particle resistivity, dielectric constant, and the physical conditions of contact (e.g., particle deformation, duration of contact, area of contact) (Wang, 1988). Unfortunately, the operating mechanism is being advertised as the "triboelectric effect," a term which is not commonly found in the scientific literature. This has confused evaluation of the technique.

The instrument is simple, consisting of a metal surface probe inserted into the stack. It has been qualitatively successful as a baghouse particulate monitor. The instrument, however, lacks a method of probe calibration and has shown problems in monitoring after electrostatic precipitators.

Electromechanical - Piezoelectricity, Loaded Beam

Electromechanical devices have been developed on the principle that the frequency of a vibrating oscillator will change if the mass of the vibrating element changes. A piezoelectric crystal, a cantilevered beam, or oscillating metal band may be used to provide the mechanical vibration. When particulate matter comes into contact with the vibrating element, it adheres to it and changes its total mass, and consequently, its vibration frequency. This mass-dependent vibration frequency is then measured as the correlation parameter.

When applied to flue gas measurements, the sample must be withdrawn isokinetically from the flue and it must be diluted to avoid condensation of the flue gas moisture. When the particles don't adhere to the vibrating element, the data is not representative. When the particles do adhere, the vibrating element will eventually become overloaded and it must be cleaned and recalibrated. In over 15 years of work on this technique, problems of cleaning and recalibration have not been successfully resolved to provide a truly continuous emission electromechanical monitor.

Performance Standards for Continuous, Particulate Mass Monitors

Although there are a number of techniques that may be suitable for continuous mass monitoring applications, the technique should meet a set of minimum performance criteria to be accepted for regulatory purposes. Parameters such as response time, zero drift, span, and span drift are commonly specified in any CEM regulation. Table 10-2 lists ISO specifications for continuous mass monitors.

Table 10-2. ISO Instrument Performance Specifications

Response time	- within the manual reference method sampling time
Zero Drift	- ± 2% of the range/month
Span	- 2-3 times the allowable emission concentration
Span Drift	- ± 2% of the range/month

From the preceding discussion, it may be realized that there is no automated method that can measure mass directly. The beta attenuation technique comes closest to this capability; however, inaccuracies due to changes in particle composition and deficiencies in instrument operation can still occur. Since there is no one best method for continuous mass monitoring, continuous mass monitoring systems should be evaluated and certified by using performance-based standards.

Performance-based standards for continuous mass monitoring systems are used in practice today in Germany (VDI, 1980 and Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety, 1992). A more general set of standards has also been prepared by the International Standards Organization (ISO) (ISO, 1993). The ISO standards are more compatible with the United States procedures for certifying CEM systems and will be used internationally.

ISO Standard - ISO 10155 - Test Methods

The ISO 10155 method ("Automated Monitoring of Mass Concentration of Particles in Stationary Source Emissions: Performance Characteristics, Test Procedures, and Specifications") includes both performance characteristics and test procedures for certifying continuous mass monitoring systems. Essentially, the method requires that a correlation be made between a manual particulate sampling method such as Method 5 or Method 17 and a parameter measured by the instrument. The method defines how a statistical correlation is to be made and defines the acceptance criteria for confidence and tolerance intervals.

Developing a correlation depends on three principal activities:

1. Varying source particulate emissions,
2. Automated monitoring
3. Manual source testing

For the first activity, emission levels can be varied in a number of ways. The following techniques can be used:

- Load levels or charging rates can be changed.
- Excess air levels can be adjusted.
- ESP fields or baghouse section can be shut off or bypassed.
- Wet scrubber pressure drop can be adjusted.
- Process failures or other control equipment failures can be simulated.
- Fuel types can be changed.

The purpose of developing the correlation should be kept in mind when planning a program for varying emissions. Particulate concentrations should not be changed just to obtain points on a graph. Instead, each change should represent a possible operating condition or control condition that would lead to higher (or lower) emission levels. Ideally, the range of variables that contribute to the regulated emissions should be incorporated in the testing program.

Changing fuels, bypassing control systems, or simulating equipment failures may all change the size distribution of the emitted particles. The resulting instrument data may or may not be well-correlated to the manual test data, depending on the extent of the changes in the measured parameters of the particles.

The ISO 10155 method specifies that a minimum of three levels of particulate mass concentration be determined and that these measurements be repeated three times to provide a total of at least nine measurements. In order to obtain varying conditions, it is recommended that process load conditions be varied.

The correlation procedure requires concurrent manual extraction of a particulate sample from the exhaust gas stream. The important point to remember in this testing procedure is that a comparison is being established between the particulate concentration and the instrument measurement parameter at a given time and under a given set of conditions. The instrument may measure an in-situ sample, or an extracted, diluted sample. Method 5 measures particulate concentration on a dry basis, and Method 17 measures on a wet basis. The in-stack filter of Method 17 will give a measurement characteristic of stack conditions, but a Method 5 out-of-stack filter may only approximate these conditions. An out-of-stack filter should be maintained at the stack temperature. If this is not possible, the concentration data should be corrected back to stack conditions on a wet basis. However, if materials are present that condense at the filter temperature but not the stack temperature, difficulties may occur in developing the correlation.

Another problem that may occur is in comparing the instrument readings with concentrations determined by manual sampling at Method 1 traverse points. An extractive beta gauge measures at one point only. A transmissometer obtains a line-averaged measurement on one diameter only, and back-scattering instruments measure only a small sampling volume. The degree of correlation between the instrument method and the manual method may be reduced if the particulate matter is non-uniformly distributed over the stack cross-section. Also, the correlation may be obtained under a set of temperature, pressure, and moisture conditions, but the instrument system may be measuring under other sets of conditions in the future. In such

cases, the actual conditions of measurement should be provided with the correlation so that the future results are not incorrectly interpreted or incorrectly compared to other studies.

The principal concern in obtaining a valid instrument-manual method correlation is too make sure that the procedures are conducted in a *representative* manner.

1. The source and control equipment should be operated under a representative set of conditions when obtaining the varying mass concentrations.
2. The automated system should measure a sample that is representative of emissions to the atmosphere.
3. The manual sampling method should extract a sample representative of that measured by the instrument system.
4. Measurements should be representative in time. Instrumented and manual measurements should be concurrent. Source operating conditions should remain stable during these measurement periods.

Statistical Analysis Procedures

The monitoring method chosen (e.g., transmissometer, beta gauge,) is acceptable for continuous monitoring if the correlation with manual source testing measurements meets specified statistical criteria. The 1993 International Standards Organization criteria are given in Table 10-3.

Table 10-3. Correlation Specifications for Continuous Mass Monitoring

Correlation Coefficient	≥ 0.95
95% Confidence Interval	± 10% of particulate emission standard
Tolerance Interval	95% confidence that 75% of values are within ± 25% of emission standard

If any of these specifications cannot be met, the sampling strategy should be re-examined. If no problems have occurred in the manual sampling, another method of instrumental measurement may have to be selected.

In the ISO statistical correlation method, either a linear or nonlinear calibration curve is established between the instrument measurements and reference method measurements. When developing the correlation, the following procedures are to be followed.

1. Initially set up the instrument. Zero and calibrate the instrument.
2. Operate the instrument for an initial 168-hour period in its normal mode, prior to conducting the manual reference method testing.
3. Check the instrument zero and span drift according to the manufacturer's instructions. Determine the drift over a period of seven days to see if it meets the specifications given in Table 10-2.

4. Develop the correlation curve.

   a. Perform measurements within normal process operation at three levels of particulate mass concentration. The levels should range from low, intermediate, and high emission values.

   b. Repeat the measurements at the three concentration levels to provide a total of at least nine measurements.

   c. If low, intermediate, and high emission values cannot be attained within normal process operation, vary emissions by adjusting the particulate emission control system (e.g. baghouse, electrostatic precipitator).

   d. Integrate the instrumental monitoring system data over the periods of manual testing.

   e. Perform the statistical calculations as defined in the method given below to determine if the monitoring system meets the specifications of Table 10-3.

In the ISO method, a least squares approach is used to develop the graphical correlation. Figure 10-6 illustrates a typical correlation developed for a transmissometer system.

The instrument reading is plotted on the abscissa and the mass concentration is plotted on the ordinate of the graph. A line of regression is drawn through the plotted points by the method of least squares. In these calculations, $\hat{y}$ is the predicted value of the mass concentration based on the calibration curve, in contrast to the empirical value, y, based on the manual reference method.

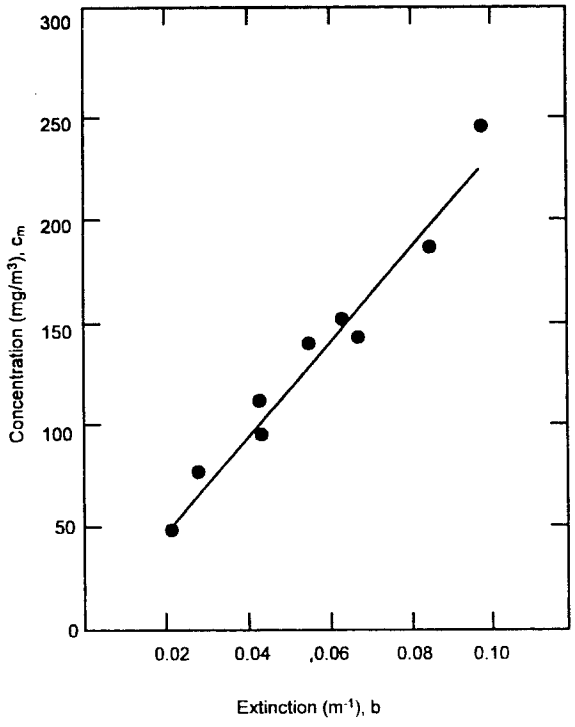

Figure 10-6. Manual reference: extinction correlation for a transmissometer continuous particulate mass monitoring system

After a regression line such as that shown in Figure 10-6 is produced, it can be used to obtain a particulate mass concentration value from a measured instrument parameter. In this example, the parameter, b, is the flue gas value of the "extinction," obtained from the transmissometer-measured optical density.

Since predictions for concentration are essentially being made from the fitted line, we would like to obtain some estimate of how good the predictions will be. This is obtained from the confidence and tolerance interval calculations. Figure 10-7 illustrates how the confidence intervals can be used.

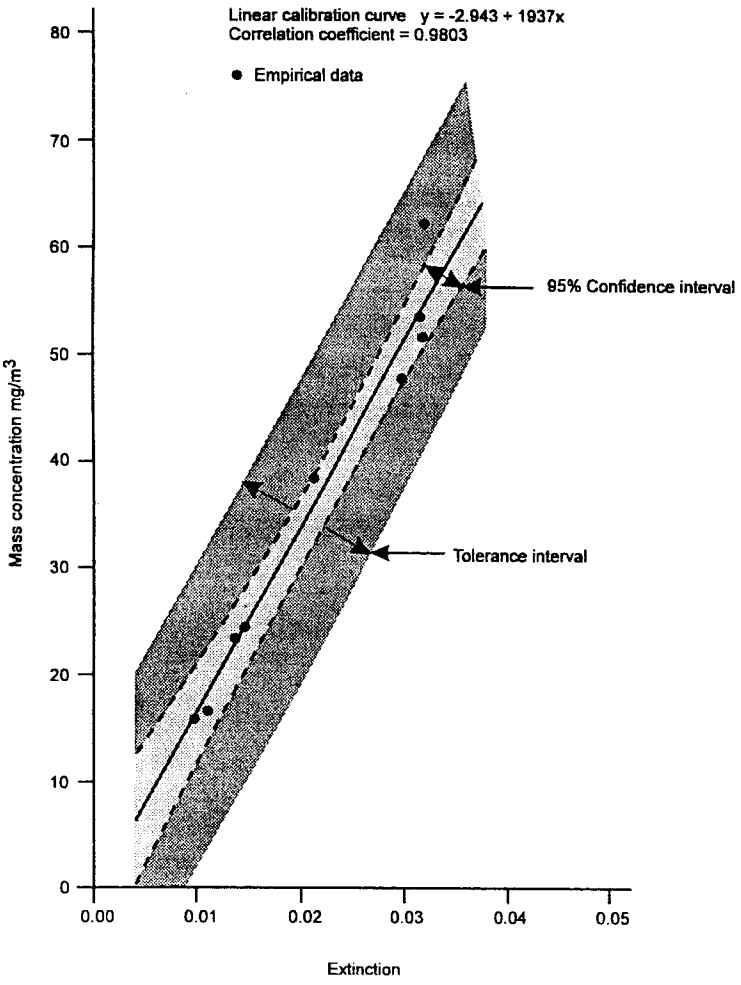

Figure 10-7. Confidence intervals and the concentration-extinction plot

The combination of the correlation coefficient, r, and the confidence intervals can give an estimate of how well the correlation technique works in a specific application. All reported data should include a graphical representation of the regression line, the 95% confidence intervals, the tolerance intervals, and the value of the correlation coefficient, r.

Note that the correlation is developed under *actual* stack conditions. If, for regulatory reasons, it is desired to report the concentration value at standard conditions, the gas law corrections should be performed after the concentration values are obtained from the graph.

Application

The approach presented here emphasizes the correlation to representative field data. Source operating conditions should be representative of normal and/or malfunction conditions, instrument measurements should be taken at a representative location, and mass concentration measurements should be made so as to be representative of the emissions sensed by the instrument.

The correlation coefficient gives an estimate of how well the concentration data correlates with the measured instrument parameter and the confidence intervals give estimates of error associated with values obtained from the graph. It should be sufficient in a regulation to state that the method is acceptable if r is equal to a chosen value, such as 0.75 or 0.90. The value of r will be essentially a regulatory decision, since the lower the value, the greater the imprecision in the values determined from the graph. If r is smaller, the confidence intervals will be larger. This has to be taken into account if the information is intended for source compliance determinations.

The correlation technique described above is valid only so long as the conditions under which a correlation was developed are representative of the source operation. Changes in operation that lead to significant changes in particle characteristics or the particle size distribution may greatly affect the slope of the correlation line. Changes in fuel, changes in control equipment, or changes in process operation may contribute to this problem. A new correlation should be developed in such situations and such guidance should be provided in the regulatory specifications. Quality assurance performance audits that check single points on a routine basis can also alleviate this problem.

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Appendix A

Equation Derivations

I. Derivation of the Equation for Molecular Weight of Stack Gas

Introduction

- Calculations involved in source sampling require knowledge of the molecular weight of a stack gas.
- Stack gas is almost always a mixture of gases.
- The apparent molecular weight of the gas mixture is a function of the composition of the mixture.
- Stack gas containing significant quantities of gaseous effluents other than oxygen, nitrogen, carbon dioxide, and water vapor should be analyzed chemically for composition and apparent molecular weight determined from this data.

Calculation of Apparent Molecular Weight of Gas Mixture

This derivation assumes the major components of the gases from a hydrocarbon combustion source to be oxygen, nitrogen, carbon dioxide, water vapor, and carbon monoxide.

The ideal gas laws

1. Boyle's law states that at constant temperature the volume of a given mass of a perfect gas of a given composition varies inversely with the absolute pressure.
2. Charles' law states that at constant volume the absolute pressure of a given mass of a perfect gas of a given composition varies directly as the absolute temperature.
3. Combining these relationships into an equation, it may be stated

$$PV = \frac{mRT}{m} \qquad \text{(A-1)}$$

Where: P = absolute pressure
T = absolute temperature
V = volume of a gas
M = molecular weight of a gas (mass/mole)
m = mass of the gas

4. Equation A-1 satisfies Dalton's law of partial pressures when

$$P_x V_{mix} = \frac{m_x R T_{mix}}{M_x} \qquad \text{(A-2)}$$

Where: P_x = partial pressure of a gas component in a mixture of nonreacting gases
V_{mix} = volume of the gas mixture
m_x = mass of a gas component
R = universal gas constant (in appropriate units)
T_{mix} = absolute temperature of the gas mixture
M_x = molecular weight (mass/mole) of a gas component

Note that $\frac{P_x V_{mix}}{T_{mix}}$ is constant only if $\frac{m_x}{M_x}$ remains constant.

Proportion by volume of a component in a gas mixture

1. Equation A-3 states that for a gas mixture

$$P_{mix} V_{mix} = \frac{m_{mix} R T_{mix}}{M_{mix}} \qquad \text{(A-3)}$$

2. Applying this relationship in Eq. A-2 and removing the common term

$$\frac{R T_{mix}}{V_{mix}}$$

it may be seen that the partial pressure of a given gas component is directly related to the mole fraction of that component in the gas mixture

$$\frac{P_x}{P_{mix}} = \frac{\frac{m_x}{M_x}}{\frac{m_{mix}}{M_{mix}}} \qquad \text{(A-4)}$$

3. At constant temperature and pressure equation A-1 may be written

$$\frac{m}{M} = \frac{PV}{RT} \qquad \text{(A-5)}$$

4. Rearranging Eq. A-2 and Eq. A-3 as Eq. A-5 and substituting in Eq. A-4

$$\frac{P_x}{P_{mix}} = \frac{V_x}{V_{mix}} \qquad \text{(A-6)}$$

5. Letting the proportion by volume (B_x) equal $\frac{V_x}{V_{mix}}$, Eq. A-6 may now be expressed

$$B_x = \frac{P_x}{P_{mix}} \qquad \text{(A-7)}$$

6. Equation A-7 gives the proportion by volume of a gas component as a function of partial pressure, which (from Dalton's law) is directly related to the mole fraction.

The apparent molecular weight of a gas mixture may now be derived using the relationship of partial pressure to the mole fraction.

1. Rewriting Equation A-2

$$M_x P_x V_{mix} = m_x R T_{mix} \qquad \text{(A-8)}$$

2. Dalton's law tells us that Eq. A-8 is actually

$$V_{mix} \Sigma P_x M_x = R T_{mix} \Sigma m_x \qquad \text{(A-9)}$$

3. $\Sigma m_x = m_{mix}$ and from Eq. A-4

$$m_{mix} = \frac{P_{mix} V_{mix} M_{mix}}{R T_{mix}} \qquad \text{(A-10)}$$

4. Substituting for Σm_x and solving for M_{mix} in Eq. A-10, we obtain

$$M_{mix} = \frac{\Sigma P_x M_x}{P_{mix}} \qquad \text{(A-11)}$$

5. Since $\frac{P_x}{P_{mix}} = B_x$, Eq. A-11 can be

$$M_{mix} = \Sigma B_x M_x \qquad \text{(A-12)}$$

II. Stack Gas Analysis Using Orsat Analyzer

1. The Orsat apparatus operates at constant proportion by volume of water vapor.
2. The Orsat method yields volume data on a dry basis (volume related to mole fraction and partial pressure).
3. The apparent molecular weight must include the water vapor component of the stack gas.
4. The stack gas moisture content may be obtained as described in the moisture content section.
5. The actual apparent molecular weight may be calculated by:

$$M_{mix} = \Sigma B_x M_x (1 - B_{ws}) + B_{ws} M_{H_2O}$$

$\Sigma B_x M_x$ = sum of dry mole fractions

B_{ws} = proportion by volume of H_2O in stack gas

M_{H_2O} = molecular weight of H_2O (A-13)

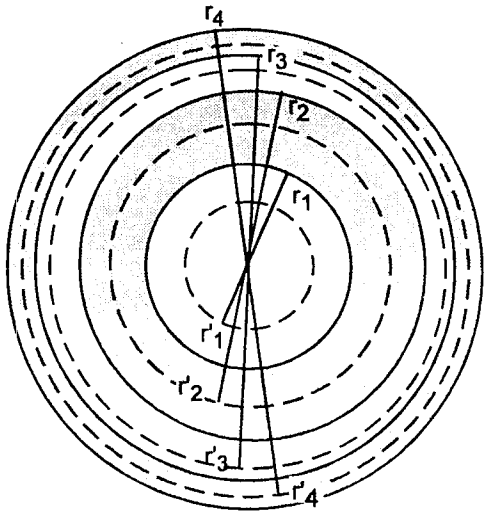
III. Derivation of Concentric Equal Areas of a Circular Duct

Traverse points are located at the centroid of an equal area in a circular duct.

A traverse point is thus a distance from the center of the duct (a radius of a concentric equal area).

The distance or radius (r'_j) for a traverse point (j) for any circular duct having (N) equal areas may be determined in the following manner:

We know that πr^2 = area of a circle.



From the preceding diagram we see:

$$\pi r_2^2 - \pi r_1^2 = \pi r_1^2 \tag{A-14}$$

which simplifies to:

$$r_1^2 = \frac{r_2^2}{2} \tag{A-15}$$

Dividing these again into equal areas

$$r'^2_2 - r_1^2 = r_2^2 - r'^2_2 \tag{A-16}$$

$$r'^2_3 - r_2^2 = r_3^2 - r'^2_3 \tag{A-17}$$

Solving Eq. A-16 and A-17 and expressing in generalized form, the locus of points r'_j separating any area (j) into two equal areas is:

$$r'^2_j = \frac{r_j^2 + (r_j - 1)^2}{2} \tag{A-18}$$

Dividing the duct of radius R into N equal areas we find:

$$\frac{\pi R^2}{N} = \pi (r_j^2 - (r_j - 1)^2)$$

$$(r_j - 1)^2 = r_j^2 - \frac{R^2}{N} \tag{A-19}$$

Substituting for $(r_j - 1)^2$ in Eq. A-19

$$r'^2_j = \frac{r_j^2 + r_j^2 - \frac{R^2}{N}}{2}$$

$$= \frac{2r_j^2 - \frac{R^2}{N}}{2}$$

$$= \frac{2Nr_j^2 - R^2}{2N}$$

Then, solving for r'_j:

$$r'^2_j = \frac{R^2\left(\frac{2Nr_j^2}{R^2} - 1\right)}{2N} \qquad \text{(A-20)}$$

$$r'_j = R\sqrt{\frac{2N\,(r'^2_j/R^2) - 1}{2N}}$$

The duct was divided into N equal areas each defined by a radius, r_1, r_2, r_3, r_4, ...r_j. r'_j is the locus of points dividing each area into two equal areas. From the diagram, N = 4 and:

$$\frac{\pi r_1^2}{\pi R^2} = 1/4$$

$$\frac{\pi r_2^2}{\pi R^2} = 2/4$$

$$\frac{\pi r_3^2}{\pi R^2} = 3/4$$

$$\frac{\pi r_4^2}{\pi R^2} = 4/4$$

generalizing:

$$\frac{r_j^2}{R^2} = \frac{j}{N} \qquad \text{(A-21)}$$

Substituting into Eq. A-20 and simplifying:

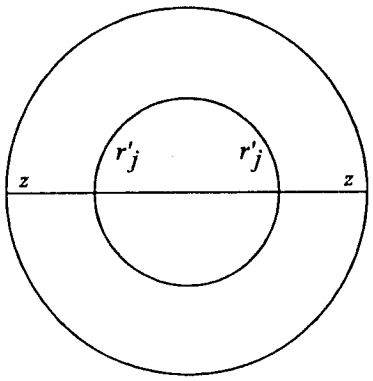
$$r'_j = R\sqrt{\frac{2N\frac{j}{N} - 1}{2N}} \qquad \text{(A-22)}$$

$$= R\sqrt{\frac{2j-1}{2N}}$$

Where: j = any locus of points dividing an equal area into two equal areas (i.e., traverse point at the centroid of an equal area)
N = number of equal areas

The percent of the duct diameter (P) (the distance from the inside wall of the duct to a traverse point) is obtained for r'_j by the following method.

a.



From the diagram

$$2r'_j + 2z = \text{Diameter } D$$

$$z = \frac{D - 2r'_j}{2}$$

b. Percent of diameter $(P) = \frac{z}{D} \times 100$

Substituting from Eq. A-23 and simplifying

$$P = \frac{(D - 2r'_j)\,100}{2} \div D$$

$$= \frac{50\,(D - 2r'_j)}{D}$$

$$P = \frac{50\left(D - 2R\sqrt{\frac{2_j - 1}{2N}}\right)}{D} \qquad \text{(A-23)}$$

Where: P = percent of diameter from inside wall to radius r'_j
N = total number of equal areas
j = specific area for which the location of points is calculated
j = 1, 2, 3, 4...from the center of duct outward

IV. Derivation of the Equivalent Diameter Equation for a Duct of Any Shape

The equivalent diameter (E_D) for a duct is also defined as the hydraulic duct diameter (H_D). The hydraulic radius (R_H) for a duct transporting fluids is defined as the cross-sectional area of that part of the channel that is filled with fluid divided by the length of the wetted perimeter.

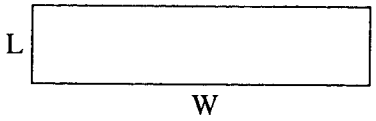
A stack gas will completely fill a duct and the entire duct perimeter will be wetted. Considering this situation for a circular duct we find:

$$R_H = \frac{\pi\left(\frac{d}{2}\right)^2}{\pi d} = \frac{\frac{d^2}{4}}{d} = \frac{1}{4d} \qquad \text{(A-24)}$$

This illustrates that the hydraulic radius of a circular duct is one-fourth the duct diameter. The equivalent or hydraulic diameter for a noncircular pipe is four times the hydraulic radius:

$$4R_H = H_D = E_D \qquad \text{(A-25)}$$

The equivalent diameter for the rectangular duct illustrated would be:



$$4R_H = 4\frac{L \times W}{2L + 2W} = 2\frac{L \times W}{L + W} = E_D \qquad \text{(A-26)}$$

which is the equation given in Method 1. This equation can be used for determining the equivalent diameter of any duct. Method 1 guidelines can then be applied.

Derivation of the Pitot Tube Equation

The pitot tube (standard or Type S) is used to measure the velocity of a gas. The pitot is actually a pressure-sensing device that allows the determination of the gas stream velocity based upon the total system energy. Figure A-1 illustrates the fluid flow around a standard pitot tube submerged in a gas stream.

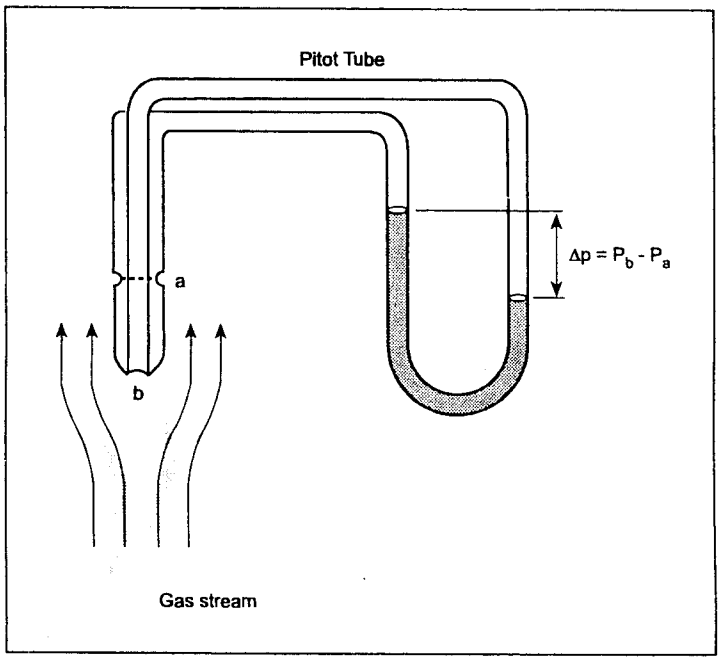


Figure A-1. Fluid flow around a standard pitot tube

Applying Bernoulli's equation to points "a" and "b" we may describe the system:

$$P_b + \frac{1}{2}\rho v_s^2 + \rho g y_1 = P_a + \frac{1}{2}\rho v_s^2 + \rho g y_2 \qquad \text{(A-27)}$$

Where:
- P_b = full ram gas pressure at point b
- P_a = free-stream gas pressure at point a - a static pressure
- ρ = gas density
- g = acceleration of gravity
- y = some elevation above a reference level, which in this case is negligible, therefore, $y_1 \cong y_2 \cong 0$
- v_s = stack gas velocity

Since $y_1 \cong y_2 \cong 0$, Eq. A-27 may be written:

$$P_b + \frac{1}{2}\rho v_s^2 = P_a + \frac{1}{2}\rho v_s^2 \qquad \text{(A-28)}$$

At point b, the gas molecules stagnate, giving up their kinetic energy. The gas velocity at b is zero ($v_s = 0$) and Eq. A-28 becomes:

$$P_b = P_a + \frac{1}{2}\rho v_s^2 \qquad \text{(A-29)}$$

The kinetic energy of the gas molecules at b has been used to perform work on the manometer fluid changing the height of the column (Δp). The knowledge that the total energy in the system is conserved allows this derivation to proceed based on a description of pressure terms in the system. The pressures in the system are balanced when:

$$P_b = P_a + \rho' g\,(\Delta p) \qquad \text{(A-30)}$$

Where: ρ' = density of the manometer fluid

Δp = change in height of the manometer column

The full ram pressure is equal to the sum of the system static pressure and the pressure of the manometer column. Rearranging terms in Eq. A-29 and Eq. A-30 we see:

$$\frac{1}{2}\rho v_s^2 = \rho' g\,(\Delta p) \qquad \text{(A-31)}$$

and

$$v_s = \sqrt{\frac{2\rho' g\,(\Delta p)}{\rho}} \qquad \text{(A-32)}$$

which describes the calculation of the gas velocity of an ideal gas in a system free of frictional energy losses.

The gas density may be described for a given gas of unknown density by using the ideal gas law. The gas density is defined:

$$\rho = \frac{\text{mass}}{\text{volume}} \qquad \text{(A-33)}$$

We know from the ideal gas law that:

$$P_s V = \frac{m}{M_s} R T_s \qquad \text{(A-34)}$$

Where: P_s = absolute pressure

V = volume

m = mass of the gas

M_s = molecular weight of the gas
R = a constant
T_s = absolute gas temperature

Rearranging terms in Eq. A-34, we obtain:

$$\frac{m}{V} = \frac{M_s P_s}{R T_s}$$

Then substituting in Eq. A-33 and Eq. A-32, we obtain:

$$v_s = \sqrt{\frac{2\rho' g \Delta p R T_s}{P_s M_s}} \qquad \text{(A-35)}$$

By using the following values in Eq. A-35, we can calculate a constant (K_p):

$$\rho'_{H_2O} = 62.428 \ \text{lb/ft}^3$$

$$g = 32.174 \ \text{ft/sec}^2$$

$$R = 21.83 \frac{\text{in. Hg} - \text{ft}^3}{\text{lb} - \text{mole} - {}^\circ\text{R}}$$

$$12 \ \text{in. } H_2O = 1 \ \text{ft}$$

$$K_p = \sqrt{\frac{2\,(62.428)\,(32.174)\,(21.83)}{12}}$$

$$= 85.486 \ \text{ft/sec} \sqrt{\frac{(\text{lb/lb} - \text{mole})\ (\text{in. Hg})}{{}^\circ\text{R} - \text{in. } H_2O}}$$

$$v_s = K_p \sqrt{\frac{T_s \ \Delta p}{P_s M_s}} \qquad \text{(A-36)}$$

The final term in our equation must account for the effect of friction and the resultant turbulence in our system. A properly constructed standard pitot tube will not be measurably influenced by frictional effects. It may be assigned a coefficient of friction $C_{p(std)}$ of units. Any other pitot tube would have to be corrected for the effects of turbulence about the tube. If we include $C_{p(std)}$ in our velocity equation we have:

$$v_s = K_p C_{p_{(std)}} \sqrt{\frac{T_s \Delta p}{P_s M_s}} \qquad \text{(A-37)}$$

The gas velocity calculated using a standard pitot tube with $C_{p(std)}$ will be equal to the velocity measured with a Type S pitot tube if we know the $C_{p(s)}$ for the Type S pitot. This may be written:

$$K_p C_{p_{(std)}} \sqrt{\frac{\Delta p_{std} T_s}{P_s M_s}} = K_p C_{p_{(s)}} \sqrt{\frac{\Delta p_s T_s}{P_s M_s}}$$

Solving for $C_{p(s)}$ we get an expression that allows us to compare the Type S pitot tube to a standard pitot tube with a known coefficient of friction:

$$C_{p_{(s)}} = C_{p_{(std)}} \sqrt{\frac{\Delta p_{std}}{\Delta p_s}} \qquad \text{(A-38)}$$

We may now use any pitot tube to measure gas velocity once we know its $C_{p(s)}$.

Derivation of Isokinetic Rate Equation

Introduction

The orifice meter setting ΔH actually correlates many factors to produce a gas velocity at the sampling nozzle equal to the velocity of the approaching gas stream.

Developing the derivation will depend on the following relationships:

- Velocity of the stack (v_s) equals the velocity of the gas entering the nozzle (v_n) at isokinetic conditions. From the pitot tube equation:

$$v_s = K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}} \qquad \text{(A-39)}$$

- The volumetric flow rate at the nozzle tip (Q_n) equals the nozzle cross-sectional area (A_n) times the gas velocity at the nozzle (v_n):

$$Q_n = A_n v_n = A_n v_s \qquad \text{(A-40)}$$

- The volumetric flow rate at the meter Q_m is related to Q_n by the ideal gas law. Assuming that the mass flow rate does not change:

$$Q_n = A_n v_s = Q_m \frac{P_m}{P_s} \frac{T_s}{T_m} \qquad \text{(A-41)}$$

- Correcting the mass flow rate at the meter for the condensation of water vapor:

$$Q_n = Q_m \frac{P_m}{P_s}\frac{T_s}{T_m}\left(\frac{1-B_{wm}}{1-B_{ws}}\right) \qquad \text{(A-42)}$$

- The flow rate at the meter is given as:

$$Q_m = K_m\sqrt{\frac{T_m \Delta H}{P_m M_m}} \qquad \text{(A-43)}$$

Derivation

Equations will be solved to give ΔH (the pressure differential across the orifice meter) for a given Δp in the stack.

From Eq. A-42

$$Q_n = Q_m\left(\frac{P_m}{P_s}\frac{T_s}{T_m}\right)\left(\frac{1-B_{wm}}{1-B_{ws}}\right) \qquad \text{(A-44)}$$

Substituting for Q_m from Eq. A-39

$$Q_n = K_m\sqrt{\frac{T_m \Delta H}{P_m M_m}}\frac{P_m}{P_s}\frac{T_s}{T_m}\left(\frac{1-B_{wm}}{1-B_{ws}}\right) \qquad \text{(A-45)}$$

Replacing $A_n v_s$ for Q_n from Eq. A-40:

$$A_n v_s = K_m\sqrt{\frac{T_m \Delta H}{P_m M_m}}\frac{P_m}{P_s}\frac{T_s}{T_m}\left(\frac{1-B_{wm}}{1-B_{ws}}\right) \qquad \text{(A-46)}$$

Substituting $A_n = \frac{\pi D_n^2}{4}$ and $v_s = K_p C_p\sqrt{\frac{T_s \Delta p}{P_s M_s}}$ and squaring both sides:

$$\left(\frac{\pi D_n^2}{4}\right)^2 K_p^2 C_p^2\left(\frac{T_s \Delta p}{P_s M_s}\right) = K_m^2\left(\frac{T_m \Delta H}{P_m M_m}\right)\frac{P_m^2}{P_s^2}\frac{T_s^2}{T_m^2}\left(\frac{1-B_{wm}}{1-B_{ws}}\right)^2 \qquad \text{(A-47)}$$

Solving for ΔH

$$\Delta H = D_n^4\left(\frac{\pi K_p C_p}{4K_m}\right)^2\left(\frac{1-B_{ws}}{1-B_{wm}}\right)^2\frac{M_m}{M_s}\frac{T_m}{T_s}\frac{P_s}{P_m}[\Delta p] \qquad \text{(A-48)}$$

Substituting $M_m = M_d(1-B_{wm}) + 18B_{wm}$ and $M_s = M_d(1-B_{ws}) + 18B_{ws}$

$$\Delta H = D_n^4\left(\frac{\pi K_p C_p}{4K_m}\right)^2\frac{(1-B_{ws})^2}{(1-B_{wm})^2}\left[\frac{M_d(1-B_{wm}) + 18B_{wm}}{M_d(1-B_{ws}) + 18B_{ws}}\right]\frac{T_m}{T_s}\frac{P_s}{P_m}[\Delta p] \qquad \text{(A-49)}$$

or

$$\Delta H = \left[846.72\ D_n^4\ \Delta H_@\ C_p^2(1-B_{ws})^2\frac{M_m}{M_s}\frac{T_m}{T_s}\frac{P_s}{P_m}\right]\Delta p$$

when assuming

$$B_{wm} = 0$$

$$\Delta H_@ = \frac{0.9244}{K_m^2}$$

$$K_p = 85.49$$

Derivation of the Isokinetic Variation Equations

The term isokinetic sampling is defined as an equal or uniform sampling of gas in motion. This is accomplished when the fluid streamlines of the stack gas are not disturbed. The Method 5 source sampling system is designed to extract an isokinetic gas and particulate sample from a stack. A 100% isokinetic source sample is taken when the gas velocity into the sampling nozzle (v_n) is equal to the velocity of the approaching gas stream (v_s):

$$\%\ \text{isokinetic variation} = \frac{v_n}{v_s} \times 100 \qquad \text{(A-50)}$$

The stack gas velocity (v_s) is measured using a pitot tube to determine the stack gas impact and static pressures. Bernoulli's theorem applied for the pitot tube and solved for gas velocity gives the expression

$$v_s = K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}} \qquad \text{(A-51)}$$

The velocity of the gas entering the source sampling nozzle is determined from the principles in the equation of continuity. Solving the equation of continuity for velocity at the nozzle, we may express the relationship

$$v_n = \frac{Q_n}{A_n} \qquad \text{(A-52)}$$

The nozzle cross-sectional area (A_n) is measured directly. The volumetric flow rate of gas at nozzle conditions (Q_n) is determined by correcting the dry gas volume metered by the orifice back to stack conditions. The water vapor condensed in the impingers must be included in this correction. Liquid water collected is converted to vapor phase volume at stack conditions to obtain the volume sampled at the nozzle.

The liquid water condensed (V_{lc}) multiplied by the water density (ρ_{H_2O}) gives the mass of water collected in the impingers

$$(V_{lc})\ (\rho_{H_2O}) = m$$

In the ideal gas law

$$PV = \frac{m}{M_{H_2O}} RT \qquad \text{(A-53)}$$

Solving the expression for volume

$$V = \frac{T}{P} \frac{mR}{M_{H_2O}}$$

The volume at stack conditions is then

$$(V_{lc})\ (\rho_{H_2O}) = m$$

$$V_{sw} = \frac{T_s m R}{P_s M}$$

$$V_{sw} = \frac{T_s}{P_s}\frac{(V_{lc})\ (\rho_{H_2O})\ R}{M_{H_2O}}$$

$$V_{sw} = \frac{T_s}{P_s}(V_{lc})\ K$$

The gas volume metered at the orifice is corrected for orifice pressure and temperature then added to V_{sw}. This total is corrected to stack conditions over the sampling time period to give Q_n

$$Q_n = \frac{\frac{T_s}{P_s}\left[(V_{lc})\ (K) + (V_m/T_m)\left(P_b + \frac{\Delta H}{13.6}\right)\right]}{\theta} \qquad \text{(A-54)}$$

Then, since

$$\%I = \frac{v_n}{v_s} \times 100$$

and

$$v_n = \frac{Q_n}{A_n}$$

we have by substitution

$$\%I = \frac{\frac{T_s}{P_s}\left[V_{lc}\ (K) + V_m/T_m\left(P_b + \frac{\Delta H}{13.6}\right)\right]}{\theta\ A_n P_s v_s}$$

Rearranging terms and including a correction for converting minutes to seconds to cancel out dimensions, we obtain the expression given in Method 5 for isokinetic variation

$$\%I = 100 \times \frac{T_s\left[V_{lc}K + V_m/T_m\left(P_b + \frac{\Delta H}{13.6}\right)\right]}{60\ \theta\ A_n P_s v_s} \qquad \text{(A-55)}$$

with the constant (K) equal to

$$K_3 = 0.002669\ \frac{\text{in. Hg} - \text{ft}^3}{\text{ml} - {}^\circ\text{R}} \quad \text{(English units)}$$

$$K_3 = 0.003454\ \frac{\text{mmHg} - \text{m}^3}{\text{ml} - {}^\circ\text{K}} \quad \text{(metric units)}$$

Derivation of the Concentration Correction Equations

After a value for the concentration of a pollutant in a flue gas stream is obtained by a reference method test, it is often necessary to correct the value to some standard set of conditions, which is done to compare the data from one source to that of another. Different stack temperatures and different amounts of excess air would make a comparison of the actual concentrations almost meaningless. Therefore, terms such as scfm for "standard cubic feet per minute" instead of acfm ("actual cubic feet per minute") and c_s (corr. 50%) instead of c_s are generally used when reporting data. Note that in reporting data in units of the standard, E ($lb/10^6$ Btu heat input), the pollutant concentration is expressed as pounds per dry *standard* cubic foot and an excess air correction is included in the F factor equation (Chapter 7). In this section, derivations for correcting a concentration to standard conditions, 50% excess air, 12% CO_2, and 6% O_2 are given.

Concentration Corrected to Standard Conditions

A concentration is expressed as weight per volume or lb/ft^3.

$$c_s = \frac{m}{V} \qquad \text{(A-56)}$$

The volume of gas passing through the nozzle will be at stack pressure and temperature. After going through the Method 5 train and meter, that temperature and pressure will change. A reference or standard set of conditions must be used, therefore, to make the data meaningful. The ideal gas law is used in these considerations

Therefore, since

$$PV = nRT \tag{A-57}$$

$$V_{stack} = \frac{nRT_{stack}}{P_{stack}} \text{ and } \quad V_{\substack{\text{corr to} \\ \text{standard} \\ \text{conditions}}} = \frac{nRT_{std}}{P_{std}}$$

For the same number of moles of gas, the volume that that number would occupy at standard conditions would be as follows.

Dividing

$$\frac{V_{corr}}{V_s} = \frac{\frac{nRT_{std}}{P_{std}}}{\frac{nRT_s}{P_s}} = \frac{T_{std}P_s}{T_sP_{std}} \tag{A-58}$$

or $$V_{corr} = V_s\frac{T_{std}P_s}{T_sP_{std}}$$

and $$c_s \text{ (at standard conditions)} = \frac{m}{V_{corr}} = \frac{m}{V_s}\frac{T_sP_{std}}{T_{std}P_s}$$

$$c_{s_{corr}} = c_s\frac{T_sP_{std}}{T_{std}P_s}$$

EPA has defined $T_{std} = 460 + 68$ °F and $P_{std} = 29.92$ in. Hg.

To report a concentration on a dry basis, the volume must be expressed as if all water had been removed. The value of B_{ws} must be known in this case.

$$V_{dry} = V_{wet} - V_{wet}B_{ws} \tag{A-59}$$

$$V_{dry} = V_{wet}(1 - B_{ws})$$

or $$c_{s_{(dry)}} = \frac{m}{V_{dry}} = \frac{m}{V_{wet}(1 - B_{ws})}$$

$$c_{s_{(dry)}} = \frac{C_{s_{(wet)}}}{(1 - B_{ws})}$$

Combining these two corrections,

$$c_{s(\text{corr to dry standard conditions})} = \frac{c_{s_{(wet)}}}{(1 - B_{ws})} \frac{T_s P_{std}}{T_{std} P_s} \quad \text{(A-60)}$$

Excess Air

Several types of concentration corrections have been devised based on the combustion characteristics of fossil fuels. Excess air is defined as that percentage of air added in excess of that required to just combust a given amount of fuel. Normally, to achieve efficient fuel combustion, more air is needed than the stoichiometric amount, i.e., one carbon atom and two oxygen molecules.

Depending on the amount of excess air, different concentrations of carbon dioxide and oxygen in the stack gas will result, as shown in Figure A-2.

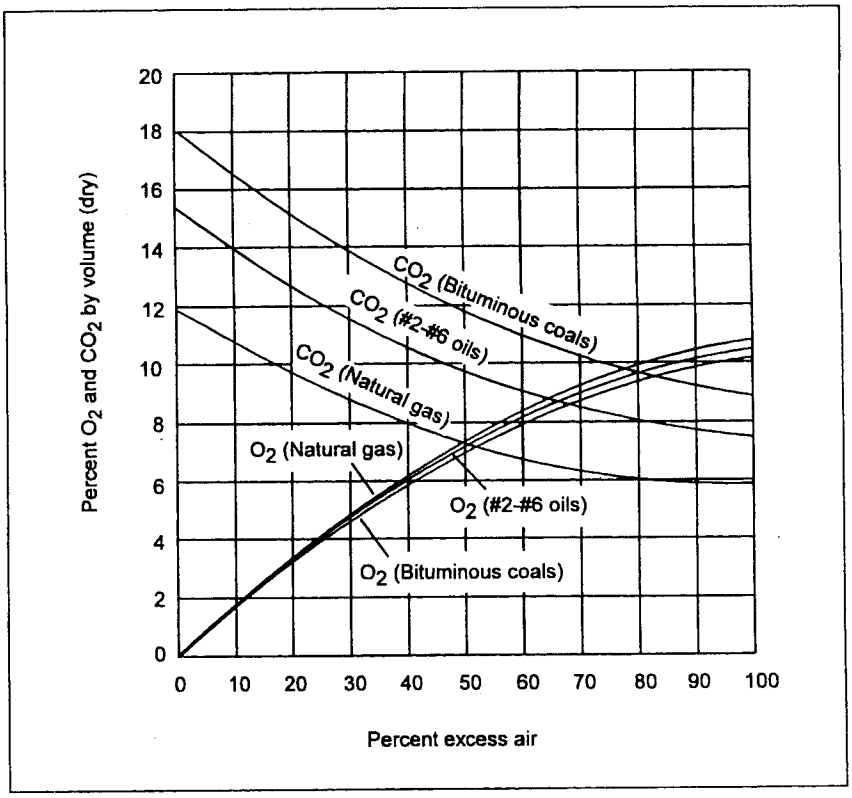


Figure A-2. Concentrations of CO_2 and O_2 in stack by amount of excess air

Since the concentration of the pollutants produced in the source could be reduced by adding more excess air, (i.e., if $c_s = m/V$, if V is increased with m constant, c_s would decrease), it has been found necessary in some cases to correct to a given excess air condition. A value of 50% excess air has been chosen as a reference condition since at one time many boilers operated at this condition. Note also that if such a correction is made, that it will account for dilution caused by air leaking in at the preheater or other duct work.

$$\%EA = \frac{\%O_2 - 0.5\%CO}{0.264\%N_2 - (\%O_2 - 0.5\%CO)} 100 \quad \text{(A-61)}$$

To derive this expression, gas volumes associated with the combustion of the fuel must be considered.

$$V_{th} = V_T - V_{EA} \quad \text{(A-62)}$$

V_{th}: stoichiometric volume of air required to consume an amount of fuel

V_T: total volume of air used

V_{EA}: volume of air in excess of $V_{Theoretical}$

Assuming that air is composed of 79% nitrogen and 21% oxygen, all oxygen would be consumed by complete stoichiometric combustion and

$$V_{N_2} = 0.79 V_{th} \quad \text{(A-63)}$$

$$V_{th} = \frac{V_{N_2}}{0.79}$$

Remember, however, that when excess air is added, the oxygen contained in that volume will not react since there will be no carbon left to consume it,

or

$$V_{O_2}(\text{remaining}) = 0.21 V_{EA} \quad \text{(A-64)}$$

The problem of incomplete combustion must also be considered in this calculation. Carbon monoxide is produced if burning conditions are not adequate.

$$C + O_2 \longrightarrow CO + \frac{1}{2} O_2$$

The amount of oxygen remaining in the flue gas must then be corrected for incomplete combustion since for each two molecules of CO produced, one molecule of oxygen will result,

$$0.5 V_{CO} = V_{O_2}(\text{incomplete combustion}) \quad \text{(A-65)}$$

Equation D-8 must be modified so that

$$V_{O_2}(\text{remaining}) = 0.21 V_{EA} + 0.5 V_{CO} \quad \text{(A-66)}$$

(Looking at this another way, one-half an oxygen molecule is released for each carbon monoxide molecule and would contribute to V_{O_2} (remaining).) Therefore, from Eq. A-66

$$V_{EA} = \frac{V_{O_2} - 0.5V_{CO}}{0.21} \tag{A-67}$$

Substituting Eq. A-63 and Eq. A-67 into Eq. A-62, we have

$$V_{th} = V_T - V_{EA} \tag{A-68}$$

$$V_{th} = \frac{V_{N_2}}{0.79} - \frac{(V_{O_2} - 0.5V_{CO})}{0.21}$$

Percent excess air is defined as that percent of air in excess of that needed for complete combustion, or

$$\%EA = \frac{V_{EA}}{V_{th}} \times 100 \tag{A-69}$$

Therefore:

$$\%EA = \frac{\dfrac{V_{O_2} - 0.5V_{CO}}{0.21}}{\dfrac{V_{N_2}}{0.79} \dfrac{V_{O_2} - 0.5V_{CO}}{0.21}} \times 100 \tag{A-70}$$

$$\%EA = \frac{V_{O_2} - 0.5V_{CO}}{0.266V_{N_2} - V_{O_2} + 0.5V_{CO}} \times 100 \tag{A-71}$$

Divide the numerator and denominator by V_T to obtain

$$\%EA = \frac{V_{O_2}/V_T - 0.5V_{CO}/V_T}{0.266V_{N_2}/V_T - V_{O_2}/V_T + 0.5V_{co}/V_T} \times 100$$

$$\%EA = \frac{\%O_2 - 0.5\%CO}{0.266\%N_2 - \%O_2 + 0.5\%CO} \times 100 \tag{A-72}$$

Concentration Corrected to 50% Excess Air

To correct a pollutant concentration to 50% excess air:

$$\frac{V_{EA} \pm \Delta V}{V_{th}} \times 100 = 50\% \text{ EA} \qquad \text{(A-73)}$$

Where: ΔV = the volume that would have to be added or subtracted to give 50% EA.

$$\Delta V = V_{EA} \pm 0.5V_{th}$$

and

$$F_{EA}V_T = V_T \pm \Delta V$$

Where F_{EA} = the proportion of V_T that would have to be changed to give 50% EA.

$$F_{EA} = \frac{V_{EA} \pm \Delta V}{V_T} = \frac{V_{th} + V_{EA} - V_{EA} + 0.5V_{th}}{V_{th} + V_{EA}}$$

$$= \frac{1.5V_{th}}{V_{th} + V_{EA}}$$

Divide the numerator and denominator by V_{th} to obtain

$$F_{EA} = \frac{1.5}{\frac{1 + V_{EA}}{V_{th}}} = \frac{150}{100 + \%EA} \qquad \text{(A-74)}$$

Therefore, since

$$c_s = \frac{m}{V_T}$$

$$c_s \text{ (corrected 50\% EA)} = \frac{m}{V_T F_{EA}} = \frac{m}{V_T \left(\frac{150}{100 + \%EA}\right)}$$

$$c_s \text{ (corr)} = c_s\left(\frac{100 + \%EA}{150}\right) \qquad \text{(A-75)}$$

It should be noted that there is a method of calculating c_s corrected to 50% EA without first calculating % EA.

Starting from

$$F_{EA} = \frac{V_T \pm \Delta V}{V_T} = 1 - \frac{(V_{EA} - 0.5V_{th})}{V_T} \qquad \text{(A-76)}$$

$$F_{EA} = 1 - \left(\frac{V_{EA} - 0.5\,(V_T - V_{EA})}{V_T} \right)$$

$$= 1 - \left(\frac{1.5V_{EA} - 0.5V_T}{V_T} \right)$$

from Eq. A-63 and Eq. A-68, we have

$$= 1 - \left[\frac{1.5\,(V_{O_2} - 0.5V_{CO}) - 0.5\left(\frac{V_{N_2}}{0.79}\right)}{V_T} \right]$$

$$= 1 - \frac{1.5\%O_2 - 0.75\%CO - 0.133\%N_2}{21}$$

and

$$c_s\,(corr) = \frac{m}{V_T F_{EA}} = c_s \frac{1}{1 - \left[\frac{1.5\%O_2 - 0.75\%CO - 0.133\%N_2}{21} \right]} \qquad \text{(A-77)}$$

It should be noted that Eq. A-75 and Eq. A-76 are not equivalent and cannot be made equivalent. They do, however, give the same answers using values characteristic of combustion sources. Note that Eq. A-69 becomes discontinuous for percent excess air as the flue gas approaches a composition corresponding to that of air (neglecting carbon monoxide). Equation A-75 also becomes discontinuous under certain conditions (e.g., $\%O_2 = 7.7\%$, $\%N_2 = 79$, % CO =0).

Correcting Concentration to 12% CO_2

The derivations for correcting a concentration to 12% CO_2 or 6% O_2 are similar to that for the 50% excess air correction. For a correction to 12% CO_2 in the flue gas:

$$\frac{V_{CO_2}}{V_T \pm \Delta V} = 0.12 \qquad \text{(A-78)}$$

or $$F_{CO_2} V_T = V_T \pm \Delta V$$

Where: ΔV = amount of air added or subtracted to give 12% CO_2

F_{CO2} = the fraction by which V_{actual} would have to be reduced or increased to do this

Substituting,

$$\frac{V_{CO_2}}{F_{CO_2} V_T} = 0.12 \qquad \text{(A-79)}$$

and

$$F_{CO_2} = \frac{\%CO_2}{12} \qquad \text{(A-80)}$$

$$c_{s12\%CO_2} = \frac{m}{V_T F_{CO_2}} = \frac{c_s}{F_{CO_2}}$$

$$c_{s12\%} = \frac{12}{\%CO_2} c_s$$

Correcting Concentration to 6% O_2

Instead of correcting a concentration to 12% O_2, a correction may be made using just the oxygen concentration. The oxygen correction is somewhat more complicated than that for carbon dioxide, since dilution air will contain oxygen.

The derivation begins with

$$\frac{V_{O_2} \pm 0.21\Delta V}{V_T \pm \Delta V} = 0.06 \qquad \text{(A-81)}$$

Where: V = the amount of air added or subtracted to give 6% O_2 in the corrected volume. Note that the term $\pm$ 0.21 ΔV is due to the oxygen contained in the air.

When F_{O_2} is the fractional amount, V_T must be changed,

$$F_{O_2} V_T = V_T - \Delta V \tag{A-82}$$

and substituting into Eq. A-79

$$\frac{V_{O_2} + 0.21 V_T - 0.21 V_T \pm 0.21 \Delta V}{V_T - \Delta V} = 0.06$$

$$\frac{V_{O_2} - 0.21 V_T + 0.21 F_{O_2} V_T}{F_{O_2} V_T} = 0.06$$

$$V_{O_2} - 0.21 V_T = 0.15 F_{O_2} V_T$$

and

$$F_{O_2} = 0.21 V_T - V_{O_2} = \frac{21 - \%O_2}{15} \tag{A-83}$$

and similarly to the previous derivations

$$c_s(6\%O_2) = \frac{15 c_s}{21 - \%O_2} \tag{A-84}$$

Note that if a correction to 3% O_2 was needed

$$c_s(3\%O_2) = \frac{18 c_s}{21 - \%O_2} \tag{A-85}$$

Appendix B

Units and Conversion Factors

Constants

Avogadro's number	6.02×10^{23} atoms/g atom
Gas constants	82.05 atm cm^3/(g mole)(°K) 1.987 cal/(g mole)(°K) 10.731 ft lb $in.^2$/(lb-mole)(°R) 0.732 ft^3 atm/(lb-mole)(°R)
(1) g mole	22.4 L ideal gas at standard temperature and pressure (0°C 1 atm)
(1) lb mole	359 ft^3 ideal gas at standard temperature and pressure (32°F 1 atm)

EPA Standard Conditions

T_{std} = 20° C (68° F)

P_{std} = 29.92 in. Hg (1 atm)

Conversion Expressions

Temperature

°K = °C + 273.16	Degrees Kelvin
°R = °F + 459.49 = 1.8 °K	Degrees Rankine
°C = 5/9 × (°F -32)	
°F = 9/5 × (°C) + 32	

Gas Concentration Units

To convert ppm to mg/m^3 at a set of standard conditions

$$mg/dscm = \frac{ppm \times MW}{22.414 \times (T_{std}/273.16)}$$

Conversion Factors

Energy

1 Btu = 1055 joule

Length

1 in. = 2.54 cm
1 ft = 0.305 m

Mass

1 g = 0.0022 lb
1 lb = 453.6 g
1 lb = 7000 grains

Mass per unit volume

1 g/m^3 = 0.0283 g/ft^3
1 lb/ft^3 = 16.02 kg/m^3

Pressure

1 atm = 1.01325 × 105 Pa = 14.696 $lb/in.^2$
= 760 torr = 407.2 in. H_2O

Power

1 Btu/hr = 0.2931 kw
1 kw = 3413 Btu/hr
1 MW = 341,300 Btu/hr

Volume

1 ft^3 = 0.02832 m^3 = 2.832 l x 10^4 cm^3
1 m^3 = 35.31 ft^3

Mass, Pressure

Multiply	By	To Obtain
Atmospheres	29.92	Inches of mercury
Atmospheres	33.90	Feet of water
Atmospheres	14.70	Pounds/Square inch
Feet of water	0.02947	Atmospheres
	0.04335	Pounds/square inch
	62.378	Pounds/square foot
Inches of mercury	0.03342	Atmospheres
	13.60	Inches of water
	1.133	Feet of water
	0.4912	Pounds/square inch
	70.727	Pounds/square foot
	345.32	Kilograms/square meter
Inches of water	0.03609	Pounds/square inch
	5.1981	Pounds/square foot
	25.38	Kilograms/square meter
Kilograms/square centimeter	0.9678	Atmospheres
	14.22	Pounds/square foot

Mass, Pressure		
Multiply	**By**	**To Obtain**
Kilograms/square meter	0.00142	Pounds/square inch
	0.20482	Pounds/square foot
	0.00328	Feet of water
	0.1	Grams/square centimeter
Kilograms	2.2046	Pounds
Pounds	453.5924	Grams
Pounds of water	0.01602	Cubic feet
Pounds of water	0.1198	Gallons
Pounds/square inch	0.06804	Atmospheres
Pounds/square inch	2.307	Feet of water
Pounds/square inch	70.31	Grams/square centimeter
Pounds/square inch	2.036	Inches of mercury

Capacity, Energy, Force, Heat		
Multiply	**By**	**To Obtain**
Btu	0.252	Kilogram-calories
Btu	9.48×10^{-4}	Watt-seconds (joules)
Btu/min	3.927×10^{-4}	Horsepower-hours
Btu/min	2.928×10^{-4}	Kilowatt-hours
Btu/min	0.02356	Horsepower
Btu/min	0.01757	Kilowatts
Btu/min	10^{-3}	Pound/hour steam
Horsepower (boiler)	33,479	Btu/hour
Horsepower (boiler)	9.803	Kilowatts
Horsepower-hours	0.7457	Kilowatt-hours
Kilowatts	56.92	Btu/minute
Kilowatts	1.341	Horsepower
Kilowatt-hours	3415	Btu
Kilowatt-hours	1.341	Horsepower-hours
Megawatts	1360	Kilogram/hour steam
Pounds/hour steam	0.454	Kilogram/hour

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