36

Source Sampling and Monitoring

I. INTRODUCTION

Air pollutants released to the atmosphere may be characterized by qualitative descriptions or quantitative analysis. For example, a plume may be characterized as brown, dense smoke, or 60% opacity. It may also be described as containing a certain concentration of particulate matter (e.g. $100\,mg\,m^{-3}$ $PM_{2.5}$). These are qualitative descriptions made by observing the effluent as it entered the atmosphere. Arguably, of most concern are the quantitative data regarding the effluent. How many parts per million of a criteria or toxic pollutant? How many kilograms per hour? How many kilograms per year? To obtain these numbers, it becomes necessary to sample or to monitor the effluent. Sampling and monitoring, therefore, are necessary for air pollution evaluation and control. In any situation concerning atmospheric emission of pollutants, source sampling or monitoring is necessary to obtain accurate data. Figure 36.1 shows a simple source test being conducted.

II. SOURCE SAMPLING

The purpose of source sampling is to obtain as representative, precise and accurate a sample as possible of the material entering the atmosphere at a

Fig. 36.1. Source test.

minimum cost. This statement needs to be examined in light of each source test conducted. The following issues should continually be considered: (1) Is the sampling and collecting of the material representative of what is actually being released? Is this the material entering the atmosphere? Sampling at the base of a tall stack may be much easier than sampling at the top, but the fact that a pollutant exists in the breeching does not mean that it will eventually be emitted to the atmosphere. Molecules can also undergo both physical and chemical changes before leaving the stack. (2) Maximum accuracy in sampling is desirable. Is maximum accuracy attainable? Decisions regarding the total effluent will be based on what was found from a relatively small sample. Only if the sample accurately represents the total will the extrapolation to the entire effluent be valid. (3) Collecting a sample is a costly and time-consuming process. The economics of the situation must be considered and the costs minimized consistent with other objectives. It makes little sense to spend $5000 on an extensive stack testing analysis to decide whether to purchase a $10 000 scrubber of 95% efficiency or to try to get by with a $7000 scrubber of 90% efficiency.

The reasons for performing a source test differ. The test might be necessary for one or more of the following reasons: (1) To obtain data concerning the emissions for an emission inventory or to identify a predominant source in the area. An example of this would be determination of the hydrocarbon release from a new type of organic solvent used in a degreasing tank. (2) To determine compliance with regulations. If authorization is obtained to construct an incinerator and the permit states that the maximum allowable particulate emission is 230 mg per standard cubic meter corrected to 12% CO_2,

a source test must be made to determine compliance with the permit. (3) To gather information which will enable selection of appropriate control equipment. If a source test determines that the emission is 3000 mg of particulate per cubic meter and that it has a weight mean size of 5 μm, a control device must be chosen which will collect enough particulate to meet some required standard, such as 200 mg per cubic meter. (4) To determine the efficiency of control equipment installed to reduce emissions. If a manufacturer supplies a device guaranteed to be 95% efficient for removal of particulate with a weight mean size of 5 μm, the effluent stream must be sampled at the inlet and outlet of the device to determine if the guarantee has been met (see Chapter 32 for a discussion of how to calculate efficiency).

III. STATISTICS OF SAMPLING

Recall that most statistics are inferential. That is, we must infer the conditions of a larger population from a much smaller sample. Thus, we must be careful in how we interpret the meaning of a sample. A sample collected at the rate of $0.3\,\mathrm{L\,min^{-1}}$ from a stack discharging $2000\,\mathrm{m^3\,min^{-1}}$ to the atmosphere is likely to include substantially large error. Another term for bias is systematic error. If the sample is truly representative, it is said to be both accurate and unbiased. If the sample is not representative, it may be biased because of some consistent phenomenon (some of the hydrocarbons condense in the tubing ahead of the trap) or in error because of some uncontrolled variation (only 1.23 g of sample was collected, and the analytical technique is accurate to ±0.5 g) [1].

For practical purposes, source testing can be considered as simple random sampling [2]. The source may be considered to be composed of such a large population of samples that the population N is infinite. From this population, n units are selected in such a manner that each unit of the population has an equal chance of being chosen. For the sample, we can determine the sample mean, $\bar{y}$:

$$\bar{y} = \frac{y_1 + y_2 + \cdots + y_n}{n} \tag{36.1}$$

If the sample is unbiased we can estimate the source mean, so that:

$$\bar{\Upsilon} = \bar{y} \tag{36.2}$$

For example, if we were to take six samples of carbon monoxide from the exhaust of an idling automobile and obtain the CO percentages as shown in Table 36.1. The sample mean is:

$$\bar{y} = \frac{1.8 + 1.6 + 1.8 + 1.9 + 1.7 + 1.8}{6} = 1.767$$

TABLE 36.1

Idling Internal Combustion Engine, CO Percentages

Test number	CO (%)
1	1.8
2	1.6
3	1.8
4	1.9
5	1.7
6	1.8

The source mean is assumed to be the same if the sample is unbiased, as seen by:

$$\bar{\Upsilon} = \bar{y} = 1.767 \tag{36.3}$$

The variance of the sample and the population (source) may also be assumed equal if the sample is unbiased. The variance is S^2, defined as:

$$S^2 = \frac{\sum_1^n (y_i - \bar{y})^2}{n-1} \tag{36.4}$$

The variance of the source is usually calculated by the formula:

$$s^2 = \frac{1}{n-1}\left[\sum y_i^2 - \frac{\left(\sum y\right)^2}{n}\right] \tag{36.5}$$

For the preceding example, this is found as follows:

$$\sum y_i^2 = 18.78, \quad \sum y_i = 10.6, \quad n = 6$$
$$s^2 = \frac{1}{6-1}\left[18.78 - \frac{(10.6)^2}{6}\right] = 0.01067$$

The standard deviation of the sample is defined as the square root of the variance. For the example, the standard deviation is:

$$s = (s^2)^{1/2} = (0.01067)^{1/2} = 0.103$$

The sample represents a population (source) which, if normally distributed, has a mean of 1.767% and a standard deviation of 0.103%. This can be illustrated as shown in Fig. 36.2.

The inference from the statistical calculations is that the true mean value of the carbon monoxide from the idling automobile has a 66.7% chance of being

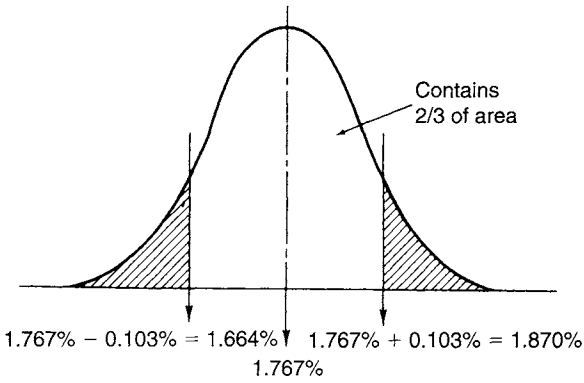

Fig. 36.2. Distribution of carbon monoxide from an automotive source.

between 1.664% and 1.870%. The best single number for the carbon monoxide emission would be 1.767% (the mean value).

Further statistical procedures can be applied to determine the confidence limits of the results. Generally, only the values for the mean and standard deviation would be reported. The reader is referred to any good statistical text to expand on the brief analysis presented here.

IV. THE SOURCE TEST

A. Test Preliminaries

The first thing that must be done for a successful source test is a complete review of all relevant background material. The test request may come in either verbal or written form. If it is verbal, it should be put into writing for the permanent record. The request may contain much or little information, but it is important to verify that it is complete and understood. Questions to ask are (1) Why should the test be made? Is it to measure a specific pollutant such as SO_2, or is it to determine less specific goal, such as identifying where a loss of a compound is occurring (e.g. between a reactor and stack) or what is causing the odor problem in the new residential area? (2) What will the test results be used for? Will it be necessary to go to court, or are the results for general information only? This may make a difference regarding the test method selected or of the necessary precision and accuracy of a given test. (3) What equipment or process is to be tested? (4) What are its operational requirements? (5) What methods would be preferred by the analytical group? (6) Are the analytical methods standard or unique? (7) Can all contaminants be sampled in a single test or will a series of test be needed (or separate tests for different target analytes)?

A literature search regarding the process and test should be conducted unless the test crew is thoroughly familiar with the source and all possible test

methods. It is important to check the regulations regarding the process and specific test procedures as a part of the search [3].

When all the background material has been reviewed, it is time to inspect the source to be tested. The inspector should be accompanied by the plant manager or someone who knows the process in detail. It is also important that any technicians or mechanics be contacted at this time regarding necessary test holes, platforms, scaffolding, power requirements, etc. During this inspection, checks should be made for environmental conditions and space requirements at the sampling site. Every visitor to the site, whether an employee of the organization or a third-party inspector, should be thoroughly familiar with all safety requirements and possible hazards. In fact, safety materials should be obtained and reviewed *before* setting foot on the premises. A number of companies require any visitor to complete safety training for certain installations. Such safety training should be completed prior to entry. Testing in a noisy or dusty place at elevated temperatures is certainly uncomfortable and possibly hazardous. Rough estimates of several important factors should be made at this time. These estimates can be noted in writing during the inspection. A simple check sheet, such as the one shown in Fig. 36.3, should be a great aid.

The information obtained during the background search and from the source inspection will enable selection of the test procedure to be used. The

SOURCE TEST PRELIMINARY VISIT CHECK LIST

Plant _____

Location _____

By _____ Date _____

1. Gas flow at test point, m/min_____, m^3/min _____
2. Gas temperature, °C_____
3. Gas pressure, mm of water (±) _____
4. Gas humidity, R. H., % _____
5. Pollutants of concern _____
6. Estimate of concentration _____
7. Any toxic materials?_____
8. Test crew needed _____
9. Site check:
   - Electric power_____ Test holes_____
   - Ambient temperature_____ Illumination _____
   - Platform_____ Scaffolding_____
   - Hoist _____ Ladders_____
   - Test date_____
10. Environmental or safety gear_____
11. Personnel involved (names)
    - Plant manager or foreman_____
    - Mechanic or electrician_____

Fig. 36.3. Source test checklist.

choice will be based on the answers to several questions: (1) What are the legal requirements? For specific sources there may be only one acceptable method. (2) What range of accuracy is desirable? Should the sample be collected by a procedure that is ±5% accurate, or should a statistical technique be used on data from eight tests at ±10% accuracy? The same is true for acceptable precision. Costs of different test methods will certainly be a consideration here. (3) Which sampling and analytical methods are available that will give the required accuracy for the estimated concentration? An Orsat gas analyzer with a sensitivity limit of ±0.02% would not be chosen to sample carbon monoxide at 50–100 ppm. Conversely, an infrared gas analyzer with a full-scale deflection of 1000 ppm would not be chosen to sample CO_2 from a power boiler. (4) Is a continuous record required over many cycles of source operation, or will one or more grab samples suffice? If a source emits for only a short period of time, a method would not be selected which requires hours to gather the required sample.

The test must be scheduled well in advance for the benefit of all concerned. The plant personnel, as well as the test crew, should be given the intended date and time of the test. It is also a good idea to let the chemist or analytical service know when the testing will be conducted so that they can be ready to do their portion of the work. It may be necessary to schedule or rent equipment in advance, such as boom trucks or scaffolding. When scheduling the test, make sure that the source will be operating in its normal manner. A boiler may be operating at only one-third load on weekends because the plant steam load is off the line and only a small heating load is being carried.

B. Gas Flow Measurement

Gas flow measurement is a very important part of source testing. The volume of gaseous effluent from a source must be determined to obtain the mass loading to the atmosphere. Flow measurement through the sampling train is necessary to determine the volume of gas containing the pollutant of interest. Many of the sampling devices used for source testing have associated gas flow indicators which must be continually checked and calibrated.

Gas flows are often determined by measuring the associated pressures. Figure 36.4 illustrates several different pressure measurements commonly made on systems carrying gases. Static pressure measurements are made to adjust the absolute pressure to standard conditions specified in the test procedure.

The quantity of gaseous effluent leaving a process is usually calculated from the continuity equation, which for this use is written as

$$Q = AV \tag{36.6}$$

where Q is the flow at the specified conditions of temperature, pressure, and humidity; A is the area through which the gas flows; and V is the velocity of the effluent gas averaged over the area.

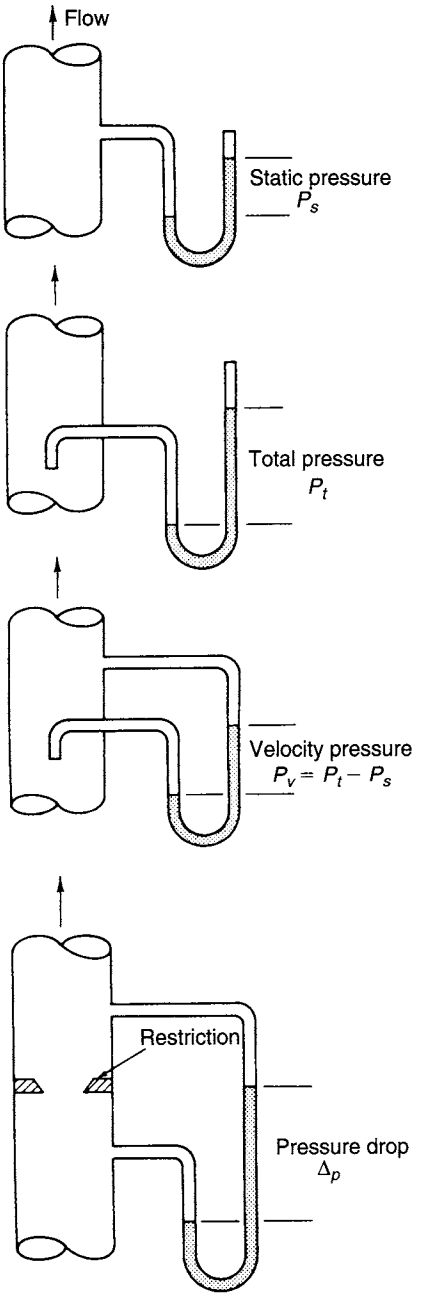

Fig. 36.4. Pressures commonly measured in flow systems.

A is commonly measured, and V determined, to calculate Q. The velocity V is determined at several points, in the center of equal duct areas, and averaged. Table 36.2 shows one commonly accepted method of dividing stacks or ducts into equal areas for velocity determinations.

For rectangular ducts, the area is evenly divided into the necessary number of measurement points. For circular ducts, Table 36.3 can be used to determine the location of the traverse points. In using this table, realize that traverses are made along two diameters at right angles to each other, as shown in Fig. 36.5.

In most source tests, the measurement of velocity is made with a pitotstatic tube, usually referred to simply as a *pitot tube.* Figure 36.6 illustrates the two types of pitot tubes in common use.

The standard type of pitot tube shown in this figure does not need to be calibrated, but it may be easily plugged in some high-effluent loading streams. The type S pitot tube shown in Fig. 36.6 does not plug as easily, but it does need calibration to assure its accuracy. The type S pitot tube is also more sensitive to alignment with the gas flow to obtain the correct reading. The velocity

TABLE 36.2

Number of Velocity Measurement Points

Stack diameter or (length + width)/2 (m)	Number of velocity measurement points
0.0–0.3	8
0.3–0.6	12
0.6–1.3	16
1.3–2.0	20
2.0→	24

TABLE 36.3

Velocity Sampling Locations, Diameters from Inside Wall to Traverse Point

	Number of equal areas to be sampled				
Point number	2	3	4	5	6
1	0.067	0.044	0.033	0.025	0.021
2	0.250	0.147	0.105	0.082	0.067
3	0.750	0.295	0.194	0.146	0.118
4	0.933	0.705	0.323	0.226	0.177
5		0.853	0.677	0.342	0.250
6		0.956	0.806	0.658	0.355
7			0.895	0.774	0.645
8			0.967	0.854	0.750
9				0.918	0.823
10				0.975	0.882
11					0.933
12					0.979

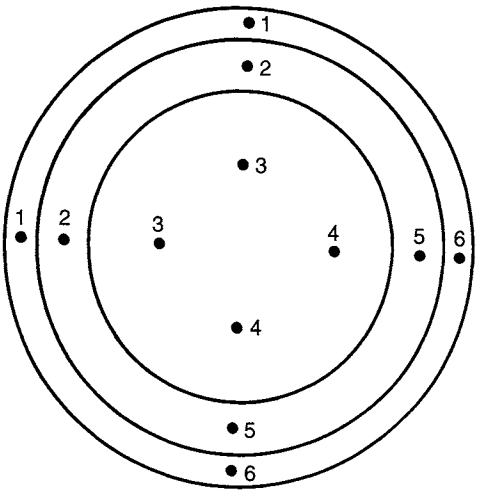

Fig. 36.5. Circular duct divided into three equal areas, as described in Table 36.3. Numbers refer to sampling points.

pressure of the flowing gas is read at each point of the traverse, and the associated gas velocity is calculated from the formula:

$$V = 420.5[(P_v/\rho)^{1/2}] \tag{36.7}$$

where V is the velocity in meters per minute, P_v is the velocity pressure in millimeters of water, and ρ is the gas density in kilograms per cubic meter. The velocities are averaged for all points of the traverse to determine the gas velocity in the duct. Velocity pressures should not be averaged, as a serious error results.

Gas velocities can also be measured with anemometers (rotating vane, hot wire, etc.), from visual observations such as the velocity of smoke puffs, or from mass balance data (knowing the fuel consumption rate, air/fuel ratio, and stack diameter).

In the sampling train itself, the gas flow must be measured to determine the sample volume. Particulates and gases are measured as micrograms per cubic meter. In either case, determination of the fraction requires that the gas volume be measured for the term in the denominator. Some sample trains contain built-in flow-indicating devices such as orifice meters, rotometers, or gas meters. These devices require calibration to assure that they read accurately at the time of the test and under test conditions.

To determine the volume through the sampling train, a positive displacement system can be used. A known volume of water is displaced by gas containing the sample. Another inexpensive procedure that works well consists of measuring the time needed for the gas to fill a plastic bag to a certain static pressure. The volume of the bag can be accurately measured under the same

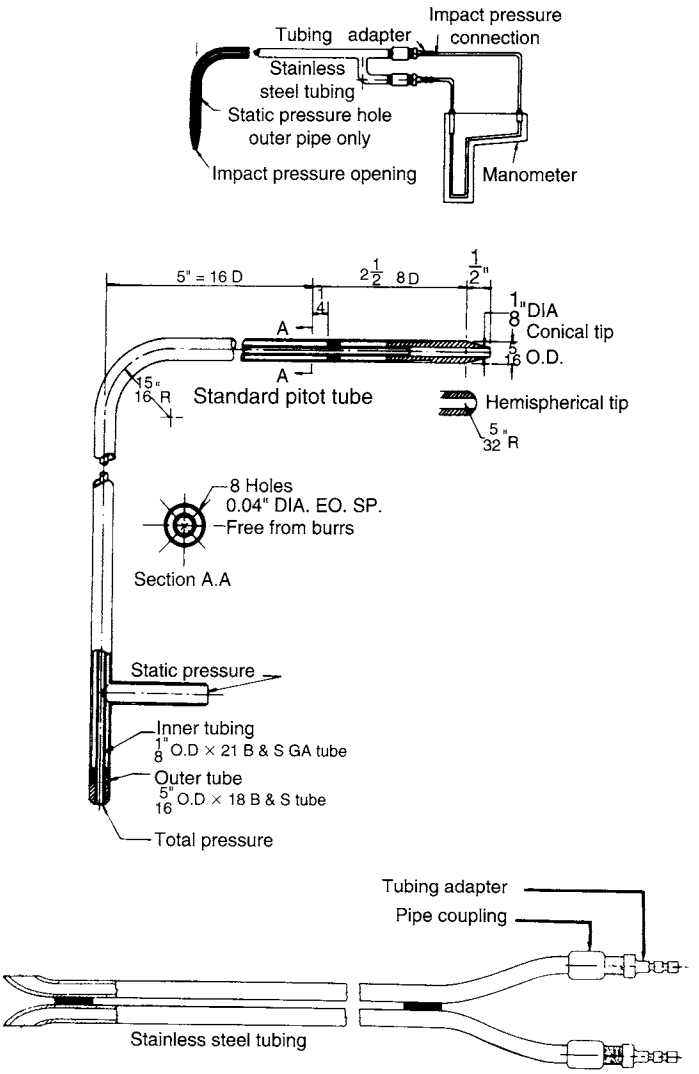

Fig. 36.6. Pitot tubes for velocity determination. *Source*: *Annual Book of Standards* [3]. *Note*: English units were used by the American Society for Testing and Materials.

conditions and hence the flow determined by dividing the bag volume by the time required to fill it.

C. Collection of the Source Sample

A typical sample train is shown in Fig. 36.7. This shows the minimum number of components, but in some systems the components may be combined. Extreme care must be exercised to assure that no leaks occur in

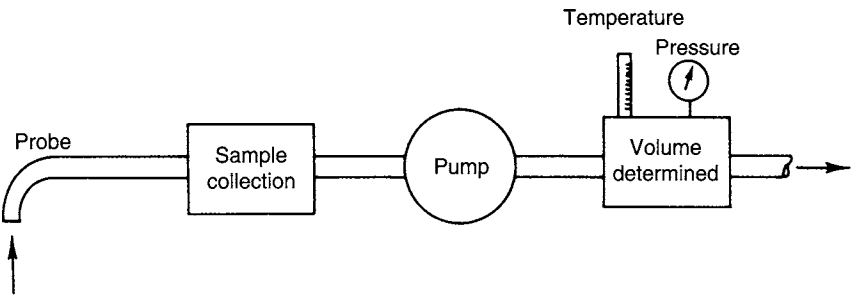

Fig. 36.7. Sampling train.

the train and that the components of the train are identical for both calibration and sampling. The pump shown in Fig. 36.7 must be both oil-less and leakproof. If the pump and volume measurement devices are interchanged, the pump no longer needs to be oil-less and leakproof, but the volume measurement will be in error unless it is adjusted for the change in static pressure. Some sampling trains become very complex as additional stages with controls and instruments are added. Many times the addition of components to a sampling train makes it so bulky and complicated that it becomes nearly impossible to use. A sampling train developed in an air-conditioned laboratory can be useless on a shaky platform in a snowstorm.

Standard sampling trains are specified for some tests. One of these standards is the system specified for large, stationary combustion sources [4]. This train was designed for sampling combustion sources and should not be selected over a simpler sampling train when sampling noncombustion sources such as low-temperature effluents from cyclones, baghouses, filters, etc. [5].

Before taking the sample train to the test site, it is wise to prepare the operating curves for the particular job. With most factory-assembled trains, these curves are a part of the package. If a sampling train is assembled from components, the curves must be developed. The type of curves will vary from source to source and from train to train. Examples of useful operating curves include (1) velocity versus velocity pressure at various temperatures [6], (2) probe tip velocity versus flowmeter readings at various temperatures, and (3) flowmeter calibration curves of flow versus pressure drop. It is much easier to take an operating point from a previously prepared curve than to take out a calculator and pad to make the calculations at the moment of the test. Remember, too, that time may be a factor and that settings must be made as rapidly as possible to obtain the necessary samples.

For sampling particulate matter, one is dealing with pollutants that have very different inertial and other characteristics from the carrying gas stream. It becomes important, therefore, to sample so that the same velocity is maintained in the probe tip as exists in the adjacent gas stream. Such sampling is called *isokinetic*. Isokinetic sampling, as well as anisokinetic sampling, is illustrated in Fig. 16.3.

If the probe velocity is less than the stack velocity, particles will be picked up by the probe, which should have been carried past it by the gas streamlines. The inertia of the particles allows them to continue on their path and be intercepted. If the probe velocity exceeds the stack velocity, the inertia of the particles carries them around the probe tip even though the carrying gases are collected. Adjustment of particulate samples taken anisokinetically to the correct stack values is possible if all of the variables of the stack gas and particulate can be accounted for in the appropriate mathematical equations.

Modern transducers and microprocessors have been used successfully to automate particulate sampling trains in order to eliminate the operating curves and manual adjustments [7]. The automated samplers adjust continuously to maintain isokinetic conditions. In addition, the microprocessor continuously calculates and displays both instantaneous sampling conditions and the total sample volume collected at any given moment. The use of the automated system with the microprocessor, therefore, eliminates both operator and calculation errors.

Several separating systems are used for particulate sampling. All rely on some principle of separating the aerosol from the gas stream. Many of the actual systems use more than one type of particulate collection device in series. If a size analysis is to be made on the collected material, it must be remembered that multiple collection devices in series will collect different size fractions. Therefore, size analyses must be made at each device and mathematically combined to obtain the size of the actual particulate in the effluent stream. In any system the probe itself removes some particulate before the carrying gas reaches the first separating device, so the probe must be cleaned and the weight of material added to that collected in the remainder of the train.

Care should be exercised when sampling for aerosols that are condensable. Some separating systems, such as wet impingers, may remove the condensables from the gas stream, whereas others, such as electrostatic precipitators, will not. Of equal concern should be possible reactions in the sampling system to form precipitates or aerosols which are not normally found when the stack gases are exhausted directly to the atmosphere. SO_3 plus other gaseous products may react in a water-filled impinger to form particulate matter not truly representative of normal SO_3 release.

When sampling particulate matter from combustion processes, it is necessary to take corresponding CO_2 readings of the effluent. Emission standards usually require combustion stack gases to be reported relative to either 12% CO_2 or 50% excess air. Adjusting to a standard CO_2 or excess air value normalizes the emission base. Also, emission standards require that the loadings be based on weight per standard cubic volume of air (usually at 20°C and 760 mmHg). In most regulations, the agency requires that the standard volume be dry, but this is not always specified.

For sampling of gases, the sample can be collected by any of several devices. Some commonly used manual methods include Orsat analyzers, absorption systems, adsorption systems, bubblers, reagent tubes, condensers, and traps.

Continuous analyzers are now more widely used than manual methods. Some types of continuous analyzers include infrared and ultraviolet instruments; flame ionization detectors; mass spectrometers; calorimetric systems; gas, liquid, and solid chromatography; coulometric and potentiometric systems; chemiluminescence; and solid-state electronic systems. Since gases undergoing analysis do not need to be sampled isokinetically, it is only necessary to insert a probe and withdraw the sample. Usually, the gas sample should be filtered to remove any accompanying particulate matter which could damage the analytical instrumentation.

For the detection and intensity of odorous substances, the nose is still the instrument usually relied upon. Since odors are gaseous, they may be sampled by simply collecting a known volume of effluent and performing some manipulation to dilute the odorous gas with known volumes of "pure" air. The odor is detected by an observer or a panel of observers. The odor-free air for dilution can be obtained by passing air through activated carbon or any other substance that removes all odors while not affecting the other gases that constitute normal air. The odor-free air is then treated by adding more and more of the odorous gas until the observer just detects the odor. The concentration is then recorded as the odor threshold as noted by that observer. The test is not truly quantitative, as much variation between observers and samples is common.

If the compound causing the odor is known and can be chemically analyzed, it may be possible to get valid quantitative data by direct gas sampling. An example would be a plant producing formaldehyde. If the effluent were sampled for formaldehyde vapor, this could be related, through proper dispersion formulas, to indicate whether the odor would cause any problems in residential neighborhoods adjacent to the plant.

Extreme care should be taken in transporting and storing the samples between the time of collection and the time of analysis. Some condensable hydrocarbon samples have been lost because the collection device was subjected to elevated temperatures during shipment. Equally disastrous is placing the sample in an oven at 105°C to drive off the moisture, only to discover that the particles of interest had a very low vapor pressure and also departed the sample. At such times, source sampling can be very frustrating.

A very important analytical tool that is overlooked by many source-testing personnel is the microscope. Microscopic analysis of a particulate sample can tell a great deal about the type of material collected as well as its size distribution. This analysis is necessary if the sample was collected to aid in the selection of a piece of control equipment. All of the efficiency curves for particulate control devices are based on fractional sizes. One would not try to remove a submicron-size aerosol with a cyclone collector, but unless a size analysis is made on the sampled material, one is merely guessing at the actual size range.

Scanning electron microscopy (SEM) may be used for analysis of particles in air (see Figures 1.4 and 36.8). Air samples are collected on filters and prepared for analysis. Filters are carbon or gold-coated and mounted so that an electron beam is directed at the sample, and emissions are measured by a detector at an angle to the electron beam. An image of the surface features on

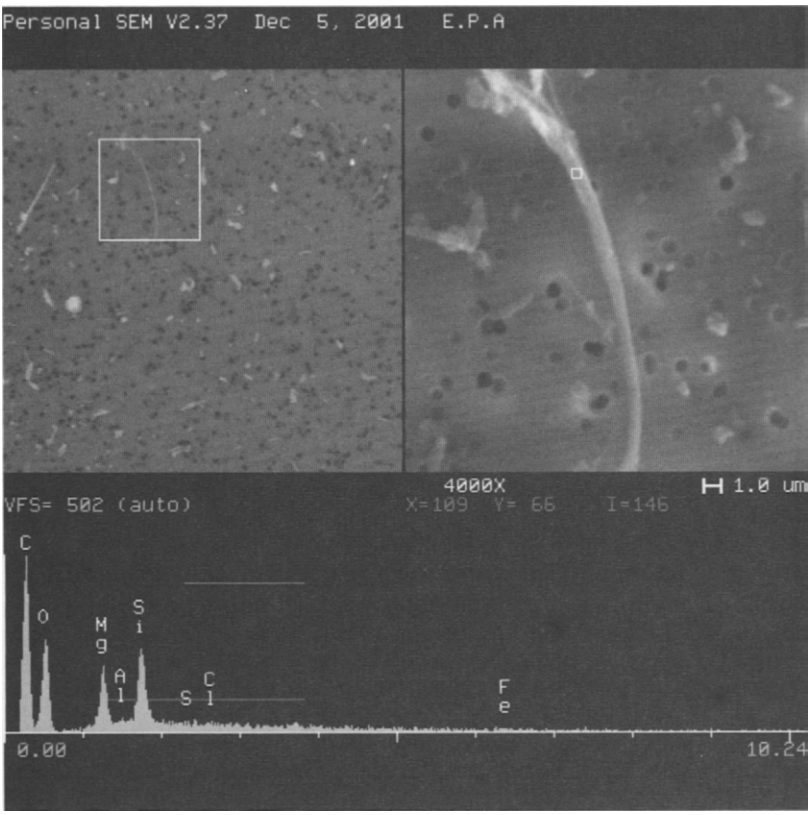

Fig. 36.8. Scanning electron micrograph (SEM) of fibers in dust collected near the World Trade Center, Manhattan, NY, in September 2001. Acquired using an Aspex Instruments, Ltd., SEM. The bottom of the micrograph represents the elemental composition of the highlighted 15-μm long fiber by energy dispersive spectroscopy (EDS). This composition (i.e. O, Si, Al, and Mg) and the morphology of the fibers indicate they are probably asbestos. The EDS carbon peak results from the dust being scanned on a polycarbonate filter. Source: US Environmental Protection Agency, 2004. Photo courtesy of T. Conner, used with permission.

the filter can then be observed at magnifications commonly up to 20 000X and higher, when needed. Many SEM systems also include energy dispersive spectrometry (EDS) to complement the morphology from SEM with the elemental composition of the particle. However, EDS will not provide individual chemical species. For example, the EDS spectrum may show that the particle consists of 20% iron and 30% zinc, but the actual compounds (e.g. iron sulfide, iron oxide, or organic iron and zinc compounds) are not known. In such cases, scientific judgment may be needed. For example, if the sample is collected near a smelter and the stack is known to generate oxidized species, metal oxides are more likely to dominate. In a reduced environment, conversely, the sulfides are likely to account for a larger part of the particle's composition.

D. Calculations and Report

Calculations that are repeatedly made can be made more accurately, and at lower cost, by using a computer. If, for example, automotive emissions are continually tested over a standardized driving cycle, a computer program to analyze the data is a necessity. Otherwise, days would be spent calculating the data obtained in hours.

For sampling a relatively small number of sources, a simplified calculation form may be used. Such forms enable the office personnel to perform the arithmetic necessary to arrive at the answers, freeing the technical staff for proposals, tests, and reports. Many of the manufacturers of source-testing equipment include example calculation forms as part of their operating manuals. Some standard sampling methods include calculation forms as a part of the method [8]. Many control agencies have developed standard forms for their own use and will supply copies on request.

The source test report is the end result of a large amount of work. It should be thorough, accurate, and written in a manner understandable to the person who intends to use it. It should state the purpose of the test, what was tested, how it was tested, the results obtained, and the conclusions reached. The actual data and calculations should be included in the appendix of the source test report so that they are available to substantiate the report if questioned.

V. SOURCE MONITORING

The monitoring of pollutant concentration or mass flow of pollutants is of interest to both plant owners and control agencies. Industry uses such measurements to keep a record of process operations and emissions for its own use and to meet regulatory requirements. Control officials use the information for compiling emission inventories, modeling of air sheds, and in some cases for enforcement.

A monitoring system is selected to meet specific needs and is tailored to the unique properties of the emissions from a particular process. It is necessary to take into account the specific process, the nature of the control devices, the peculiarities of the source, and the use of the data obtained [8].

Source monitoring can best be treated as a system concept ideally consisting of six unit operations, as shown in Table 36.4. In the United States, installation and operation of monitoring systems have been prescribed for a number of industries, as shown in Table 36.5.

A. Types of Monitors

Continuous emission monitors (CEMs) for plume opacity have been required on all utility, fossil fuel-fired, steam generators (over 264 MJ)

TABLE 36.4

System Concept of Stationary Source Measurements

Operation	Objective
Sampling site selection	Representative sampling consistent with intended interpretation of measurement
Sample transport (when applicable)	Spatial and temporal transfer of sample extract with minimum and/or known effects on sample integrity
Sample treatment (when applicable)	Physical and/or chemical conditioning of sample consistent with analytical operation, with controlled and/or known effects on sample integrity
Sample analysis	Generation of qualitative and quantitative data on pollutant or parameter of interest
Data reduction and display	Calibration and processing of analog data and display of final data in a format consistent with measurement objectives
Data interpretation	Validly relating the measurement data to the source environment within the limitations of the sampling and analytical operations

Source: Nader [9].

constructed in the United States since December 1971. These monitors are *in situ* opacity meters which measure the attenuation of a light beam projected across the stack (see Fig. 27.2). Remote-sensing monitors have been developed, but these have not yet been approved as equivalent to the *in situ* opacity monitors. CEMs for gaseous emissions are also available and required for certain facilities. Figure 36.9 illustrates the various approaches to monitoring particulate opacity and gaseous emissions.

B. Quality Assurance in Monitoring

In order to assure that the source is being accurately monitored, several requirements must be met [1]. Some of these requirements, which assure representative, noncontaminated samples, are shown in Table 36.6.

C. Monitoring of Particulate Emissions

The most common monitoring of particulate matter is for light attenuation (opacity). Less frequently used methods exist for monitoring mass concentration, size distribution, and chemical composition.

Opacity is a function of light transmission through the plume. Opacity is defined as follows:

$$\text{Opacity} = (1 - I/I_0) \times 100 \tag{36.8}$$

where I_0 is the incident light flux and I is the light flux leaving the plume. Techniques for monitoring visible emissions (opacity) are listed in Table 36.7.

TABLE 36.5

Source Emissions Requiring Continuous Monitoring by United States New Source Performance Standards

Source	Pollutant						Scrubber pressure loss and water pressure	Flow rate
	SO_2	NO_x	CO	Opacity	H_2S	Total reduced sulfur		
Electric power plants	x	x		x				
Sulfuric acid plants	x							
Onshore natural gas processing SO_2 emissions	x							
Nitric acid plants		x						
Petroleum refineries	x		x	x	x	x		
Iron and steel mills (BOF)[a]							x	
Steel mills (electric arc)				x				x
Ferroalloy production				x				
Glass manufacturing plants				x				
Portland cement plants				x				x
Primary copper smelters	x			x				
Primary zinc smelters	x			x				
Primary lead smelters	x			x				
Coal preparation plants							x	
Wet process phosphoric acid plants							x	
Superphosphoric acid plants							x	
Diammonium phosphate plants							x	
Triple superphosphate plants							x	
Granular triple superphosphate plants							x	
Phosphate rock plants				x			x	
Metallic mineral processing plants							x	
Nonmetallic mineral processing plants							x	
Kraft pulp mills				x		x	x	x
Gas turbines[b]								
Lime kilns[c]				x		x	x	
Ammonium sulfate plants							x	
Lead–acid battery manufacture							x	

[a] BOF: basic oxygen furnace.
[b] Monitor sulfur and nitrogen content of fuel and water/fuel ratio.
[c] Also monitor scrubber liquid flow rate.
Source: Code of Federal Regulations [8].

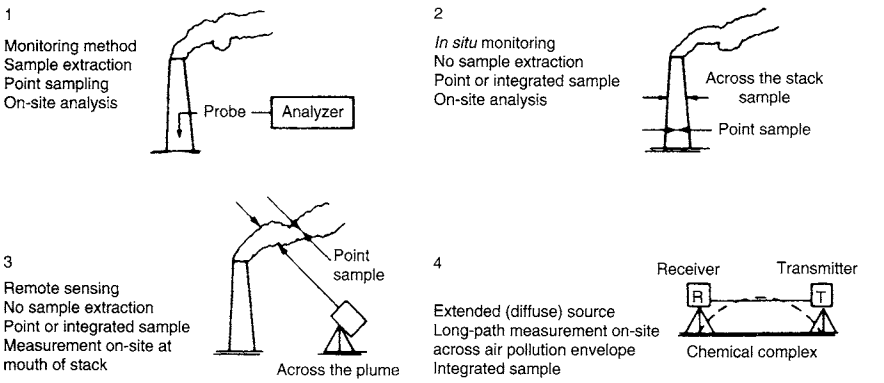

Fig. 36.9. Sampling approaches to monitoring source emissions. *Source*: Nader [9].

TABLE 36.6

Stationary Source Monitoring Requirements

Requirement	Method of attainment
Maintain gas temperature above the water or acid dew point	Heat lines or dilute with dry air
Remove water before sample enters instrument	Refrigerate or desiccate sample
Remove particulate matter before sample enters instrument	Use cyclone or filter in sample line
Dilute sample to lower the temperature to an acceptable level for the instrument	Air dilute with necessary blowers, flow measurement, and control systems
Maintain integrity of particulate sample (mass, size, and chemical composition)	Use isokinetic sampling, refrigerated sample transport, and careful handling to minimize physical or chemical changes

TABLE 36.7

Opacity Monitoring Techniques

Method of analysis	Measurement system
In-stock opacity	Optical transmissometer
Plume opacity	Lidar (light detection and ranging)
Selective opacity (for fine particles)	Extractive with light-scattering determination

D. Monitoring of Gaseous Emissions

Gas-monitoring systems are more widely used than particulate monitoring systems. They can also be used for both emission compliance monitors and process control systems. Gas monitors may be of either the *in situ* or the

TABLE 36.8

Gas Emission Monitoring Systems

Analytical scheme	Sampling approach[a]	Pollutant capability[b]
Chemielectromagnetic		
Colorimetry	E	SO_2, NO_x, H_2S, TS
Chemiluminescent	E	NO_x
Electromagnetic/electrooptical		
Flame photometry	E	SO_2, H_2S, TRS, TS
Nondispersive infrared	E	SO_2, NO, CO, HC, CO_2
Nondispersive, ultraviolet and visible	E	SO_2, NO_x, NH_3, H_2S
Dispersive, infrared and ultraviolet	I	SO_2, NO, CO, CO_2, HC, H_2S
Dispersive, infrared and ultraviolet	E	SO_2, CO, CO_2, HC, NO
Correlation, ultraviolet	I	SO_2
Correlation, ultraviolet and visible	R	SO_2, NO_x
Derivative, ultraviolet	I	SO_2, NO_2, NO, O_2, NH_3, CO
Fluorescence, ultraviolet	E	SO_2
Electrical		
Conductivity	E	SO_2, NH_3, HCl
Coulometry	E	SO_2, H_2S, TRS
Electrochemical	E, I	SO_2, NO_x, CO, H_2S, O_2
Flame ionization	E	HC
Thermal		
Oxidation	E	CO
Conductivity	E	SO_2, NH_3, CO_2
Hybrid		
Gas chromatography, flame ionization	E	CO, HC
Gas chromatography, flame photometry	E	Sulfur compounds

[a] E, extractive; I, *in situ*; R, remote.
[b] HC, hydrocarbons; TRS, total reduced sulfur; TS, total sulfur; NO_x, total oxides of nitrogen, but system may be specific for NO, NO_2, or both.
Source: Nader [9].

extractive type and use the approaches illustrated in Fig. 36.9. Table 36.8 lists the various types of gas-monitoring systems.

E. Data Reduction and Presentation

Continuous monitors usually indicate the pollutant concentration on both an indicator and a chart recording. This provides a visual indication of the instantaneous emissions, along with a permanent record of the quantitative emissions over a period of time. The monitoring system may also be equipped with an alarm device to signal the operator if the allowable emission level is being exceeded. Data-logging systems coupled with microprocessors are popular. These systems can give instantaneous values of the variables and pollutants of interest, along with the averages or totals for the period of concern.

REFERENCES

1. *Quality Assurance Handbook for Air Pollutant Measurement Systems*, Vol. III, *Stationary Source Specific Methods*, EPA-600/4-77-027b. US Environmental Protection Agency, Research Triangle Park, NC, 1977.
2. Stern, A. C. (ed.), *Air Pollution*, 3rd ed., Vol. III. Academic Press, New York, 1977.
3. *1981 Annual Book of ASTM Standards, Part 26, Gaseous Fuels; Coal and Coke; Atmospheric Analysis*. American Society for Testing and Materials, Philadelphia, PA, 1981.
4. Environmental Protection Agency—Standards of performance for new stationary sources. *Fed. Regist.* **36** (247), 2488 (1971).
5. Boubel, R. W., *J. Air. Pollut. Control Assoc.* **21**, 783–787 (1971).
6. Baumeister, T. (ed.), *Marks' Standard Handbook for Mechanical Engineers*, 8th ed. McGraw-Hill, New York, 1978.
7. Boubel, R. W., Hirsch, J. W., and Sadri, B., Particulate sampling has gone automatic, *Proceedings of the 68th Annual Meeting of the Air Pollution Control Association*, Pittsburgh, PA, 1975.
8. Code of Federal Regulations, Chapter I, Part 60, Standards of performance for new stationary sources, 1992.
9. Nader, J. S., Source monitoring, in *Air Pollution* (Stern, A. C., ed.), 3rd ed., Vol. III. Academic Press, New York, 1976.

SUGGESTED READING

Brenchley, D. L., Turley, C. D., and Yarmac, R. F., *Industrial Source Sampling*. Ann Arbor Science Publishers, Ann Arbor, MI, 1973.

Cooper, H. B. H., and Rossano, A. T., *Source Testing for Air Pollution Control*. Environmental Sciences Services Division, Wilton, CT, 1970.

Frederick, E. R. (ed.), *Proceedings, Continuous Emission Monitoring: Design, Operation, and Experience, Specialty Conference*. Air Pollution Control Association, Pittsburgh, PA, 1981.

Morrow, N. L., Brief, R. S., and Bertrand, R. R., *Chem. Eng.* **79**, 85–8 (1972).

QUESTIONS

1. During a pitot traverse of a duct, the following velocity pressures, in millimeters of water, were measured at the center of equal areas: 13.2, 29.1, 29.7, 20.6, 17.8, 30.4, 28.4, and 15.2. If the flowing fluid was air at 760 mmHg absolute and 85°C, what was the average gas velocity?
2. Would you expect errors of the same magnitude when sampling anisokinetically at 80% of stack velocity as when sampling anisokinetically at 120% of stack velocity? Explain.
3. Suppose a particulate sample from a stack is separated into two fractions by the sampling device. Both are sized microscopically and found to be lognormally distributed. One has a count mean size of 5.0 μm and a geometric deviation of 2.0. The other has a count mean size of 10.0 μm and a geometric deviation of 2.2. Two grams of the smaller-sized material were collected for each 10 g of the larger. What would be reported for the weight mean size and geometric deviation of the stack effluent?
4. A particulate sample was found to weigh 0.0216 g. The sample volume from which it was collected was 0.60 m^3 at 60°C, 760 mmHg absolute, and 90% relative humidity. What was the stack loading in milligrams per standard cubic meter?

5. A particulate sample was found to contain 350 mg m^{-3}. The CO_2 during the sampling period averaged 7.2%. If the exhaust gas flow was 2000 $m^3 min^{-1}$, what would be the particulate loading in both milligrams per cubic meter and kilograms per hour, corrected to 12% CO_2?
6. Give an example of how opacity monitoring of a coal-fired boiler could be used to improve combustion efficiency.
7. An opacity monitor is set so that the incident light is 100 units. Prepare a graph of the percentage of opacity versus the light flux leaving the plume (opacity, 0–100%; exiting light flux, 0–100 units).
8. List the advantages and disadvantages of both *in situ* and extractive gas monitors.
9. Discuss the advantages and disadvantages of one-time source testing for a specific emission versus continuous monitoring of the same emission.