AIR MONITORING FOR TOXIC EXPOSURES

Second Edition

HENRY J. MCDERMOTT
H. J. McDermott, Inc.
Moraga, California

WILEY-INTERSCIENCE

A JOHN WILEY & SONS, INC., PUBLICATION

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PREFACE

Shirley Ness contributed a wealth of valuable material in the first edition of *Air Monitoring for Toxic Exposures*. I want to acknowledge her contribution to occupational and environmental health in her excellent overview of the entire topic of air sampling.

When gathering information to revise the first edition, I was impressed by the advances in sampling technology that have occurred in the 15 years since Shirley researched the first edition. Today even pocket-size direct-reading instruments have data-logging capability, which allows them to collect integrated exposure measurements. We are also seeing instruments designed be used with hand-held computers in the field so that data are stored directly in the computer rather than downloaded in a separate step. Sensor technology, microprocessors, and miniaturization have increased the range of direct-reading instruments available, and they also allow sophisticated instruments such as GC/mass spectrometers and Fourier transform infrared devices to be field-portable. Colorimetric systems continue to develop: More sensitive detector tubes that measure more chemicals are on the market, and useful accessories such as battery-powered sampling pumps have been introduced.

The need air sampling to be performed during terrorism events is another reflection of the changing times since the first edition was published. Air sampling can help to determine whether an event has actually occurred and, if so, identify the agent(s) and quantify exposure levels. To address this need, a completely new chapter on air sampling during emergency response including terrorism events has been added.

I appreciate the help of equipment manufacturers and others in providing the photographs used in this edition. Of course there are many quality instruments available other than the ones highlighted in this book; it was not feasible to include all options.

There are a few people who deserve special thanks. Bob Esposito, Jonathan Rose and Lisa Van Horn of John Wiley & Sons were very helpful. Jack Chou of International Sensor Technology graciously permitted use of many diagrams and Appendix C on sensor calibration from his fine book *Hazardous Gas Monitors—A Practical Guide to Selection, Operation and Applications*. Dr. E. C. Kimmel provided the elec-

tron microscope photographs of smoke particles to illustrate Chapter 7. Michelle Filby of SKC, Inc. spent extra time providing many photographs in a format that I could use. Galson Laboratories furnished their table of guidelines for air sampling and analysis for Appendix D. Also, a special salute goes to C. W. Pots for editorial advice and general encouragement.

This edition is "dedicated" to all of the air sampling practitioners who perform air monitoring for toxic exposures. They include industrial hygienists, environmental specialists, safety and health technicians, safety professionals, environmental health specialists, chemists, laboratory technicians, firefighters, emergency responders, hazardous materials specialists, and others. Each group has unique skills and background; together they work to help protect people and the environment. I hope that this book is helpful to them.

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PART I

BACKGROUND CONCEPTS FOR AIR MONITORING

CHAPTER 1

AIR MONITORING OVERVIEW

The field of air monitoring is broad from every perspective: the reason for performing the monitoring; the types of air contaminants and the potential hazards they pose; the monitoring techniques and equipment; and the background and skills of the people who carry out the sampling. The purpose of this chapter is to give a general overview of the entire topic in order to make the remaining chapters in the book easier to understand and apply. Remember, almost everything summarized in this chapter is covered in more detail later in the book. Additionally, many of the terms used in air monitoring can have more than one meaning, so this chapter presents the nomenclature that will be used throughout the book.

The decision to perform air monitoring for toxic exposures is based on either (a) a regulatory standard that requires monitoring or (b) a hazard evaluation that indicates monitoring is needed to identify or quantify exposures. Hazard evaluations recognize that chemical, physical, and biological agents can cause injury, disease, or death. Potential hazards are evaluated by skilled practitioners based on:

- Toxicity of the material—the material's inherent capacity to cause disease or injury.
- Physical or chemical form of the contaminant—whether a gas, vapor, or particulate matter (aerosol).
- Route(s) of exposure—inhalation, skin, or ingestion.
- Physical hazards—such as the fire or explosion risk posed by the material.
- Likely dose based on an understanding of the exposures that occur as part of the industrial process, from predicable release scenarios, or other exposure situations.
- Effectiveness of exposure controls (engineering interventions, safe work practices, or personal protective equipment) in preventing harmful exposures.

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An illustration of regulatory-driven monitoring is the U.S. Federal OSHA Benzene Standard. It requires monitoring to determine exposure levels for workers handling benzene-containing liquids containing >0.1% benzene, except for specific situations listed in the standard that have been shown not to cause significant exposures. As an illustration of a typical air sampling "case study," the Federal OSHA Benzene Standard will be cited throughout this chapter as it impacts air monitoring for occupational exposures. Table 1.1 lists the aspects of the standard[1] that are related to exposure monitoring.

AIR SAMPLING IN PERSPECTIVE

Air sampling (or monitoring) is one part of an overall process called *exposure assessment*, which is aimed at defining an individual's or a group's exposure to chemical, physical, and biological agents in the environment. The source of the agents may be natural, industrial operations, vehicle emissions, homes, agriculture, demolition operations, waste disposal sites, accidental releases, intentional releases from terrorism or similar events, or others. The population whose exposure is being measured may be employees of the organization

TABLE 1.1. Air Monitoring-Related Requirements—OSHA Benzene Standard

The following items are requirements from the U.S. Federal OSHA Benzene Standard that relate to exposure monitoring. These requirements are a good illustration of how exposure monitoring applies in the occupational setting. Also see Table 1.3, which is a summary of sampling and analytical methods for benzene from the standard.

General

- The standard establishes two permissible exposure limits (PELs):
  - Time-weighted average limit (TWA): 1 ppm as an 8-hour time-weighted average.
  - Short-term exposure limit (STEL): 5 ppm as averaged over any 15-minute period.
- The "action level," which requires some follow-up actions, is 0.5 ppm TWA. Additionally, the term "employee exposure" means exposure to airborne benzene which would occur if the employee were not using respiratory protective equipment.
- STEL compliance is determined from 15-minute employee breathing zone samples measured at operations where there is reason to believe that exposures are high. Objective data, such as measurements from brief period measuring devices, may be used to determine where STEL monitoring is needed.
- Except for "initial monitoring," in cases where one shift will consistently have higher employee exposures for an operation, monitoring is required only during the shift on which the highest exposure is expected.

Exposure Monitoring

- *Initial monitoring* is to cover each job on each work shift and be completed within 30 days of the introduction of benzene into the workplace. For TWA exposures:
  - At or above the action level but at or below the TWA, the monitoring is to be repeated annually.
  - Above the TWA, the monitoring is to be repeated at least every six months.
  - Below the action level no follow-up monitoring for that employee is required unless conditions change or during spills or releases.
- The monitoring schedule may be reduced from every six months to annually for any employee for whom two consecutive measurements taken at least 7 days apart indicate that the employee exposure has decreased to the TWA or below, but is at or above the action level.

TABLE 1.1. ***Continued***

- Monitoring for the STEL shall be repeated as necessary to evaluate exposures of employees subject to short term exposures.
- Periodic monitoring may be discontinued if at least two consecutive of the required periodic monitoring exposures, taken at least 7 days apart, are below the action level, unless conditions change or during spills or releases.
- Whenever spills, leaks, ruptures or other breakdowns occur that may lead to employee exposure, monitoring is required (using area or personal sampling) after the cleanup or repair to ensure that exposures have returned to the level that existed prior to the incident.

Other Monitoring-Related Requirements

- Employees are to be notified of monitoring results within 15 working days after the results are received, either individually in writing or by posting results in an appropriate, accessible location. Whenever the PELs are exceeded, the notification must describe the corrective action being taken to reduce the employee exposure to or below the PEL.
- Exposure controls are required for exposures above the PELs.
- Respiratory protection, if used, is to be selected based on exposure levels:

Airborne Concentration or Condition of Use	Respirator Type
≤10 ppm	• Half-mask air-purifying respirator with organic cartridge.
≤50 ppm	• Full facepiece respirator with organic cartridges or chin-style canister.
≤100 ppm	• Full facepiece powered air-purifying respirator with organic cartridges
≤1000 ppm	• Supplied air respirator with full facepiece in positive-pressure mode.
>1000 ppm or unknown concentration	• Self-contained breathing apparatus with full facepiece in positive pressure mode. • Full facepiece positive-pressure supplied-air respirator with auxiliary self-contained air supply.
Escape	• Any organic vapor gas mask. • Any self-contained breathing apparatus with full facepiece.
Firefighting	• Full facepiece self-contained breathing apparatus in positive pressure mode.

- Medical surveillance program (meeting the requirements of the standard) must be made available for employees who are or may be exposed to benzene at or above the action level 30 or more days per year; for employees who are or may be exposed to benzene at or above the PELs 10 or more days per year; and for employees who have been exposed to more than 10 ppm of benzene for 30 or more days in a year prior to the effective date of the standard when employed by their current employer. Information provided to the physician is to include the employee's actual or representative exposure level.
- Employees require initial training. If exposures are above the action level, employees are to be provided with information and training at least annually thereafter.
- A record of all exposure monitoring is to be maintained for 30 years. This record is to include:
  - The dates, number, duration, and results of each of the samples taken, including a description of the procedure used to determine representative employee exposures;
  - Description of the sampling and analytical methods used;
  - Description of the type of respiratory protective devices worn, if any; and
  - Name, social security number, job classification and exposure levels of the employee monitored and all other employees whose exposure the measurement is intended to represent.
- Observation of monitoring: Employees, or their designated representatives, are to have an opportunity to observe the measuring or monitoring of employee exposure to benzene conducted pursuant to the standard.

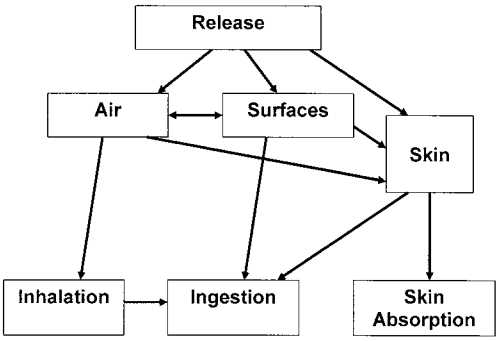

Figure 1.1. Pathways showing how occupational and environmental releases can result in human exposure to contaminants.

releasing the contaminant (e.g., occupational exposure), members of the general population, emergency responders or hazardous materials specialists, or another group. Figure 1.1 shows a general model of exposure pathways typical of airborne release of toxic contaminants. For very comprehensive exposure assessments, Figure 1.1 might have to be expanded to include other pathways such as ingestion of contaminated water.

The topic of exposure assessment is a technical specialty by itself;[2] more information on the topic is contained in Chapter 3. The focus of this book is on the air monitoring phase of the exposure assessment process.

AIR SAMPLING STRATEGY AND PLAN

Air samples are collected for a variety of purposes and under different circumstances:

- *Occupational exposures*—generally the contaminants are known and monitoring is performed to evaluate legal compliance or conformance with recommended exposure limits. Emphasis is on collecting enough samples to adequately describe the *typical* average work shift and peak short-term exposure patterns and also describe the *worst-case* exposures.
- *Community environment*—longer-term sampling to assess community exposure to a wide variety of expected pollutants including industrial emissions, vehicle exhaust and evaporated fuel components, airborne dust, and so on. Short-term sampling is performed to (a) identify odors or irritants based on community complaints or (b) identify toxic components in smoke or uncontrolled releases.
- *Indoor air quality evaluations*—long- and short-term monitoring of carbon dioxide, humidity, carbon monoxide, asbestos, organic vapors, bioaerosols, and radon and its progeny.
- *Emergency response* (including terrorism events)—sampling to identify unknown agents; direct reading tests for flammable vapors and other common contaminants to evaluate immediate hazards; exposure measurements to document exposures to responders to hazardous material releases and other emergencies and to determine the appropriate level of respiratory protective gear.

The air sampling approach in each of the above applications will be different. For example, in occupational exposures there is a choice about whether to carry out a statistical sampling campaign to gather enough samples for a valid statistical analysis of results or to identify and evaluate expected "worst-case" exposure patterns to ensure compliance. For emergency responders the emphasis is on preplanning to ensure that the right monitoring equipment is available and is deployed quickly to identify/assess potential hazards. During an emergency response, sampling devices that give immediate readings at the scene are preferred (where feasible) over possibly

more accurate sampling methods that require laboratory analysis. However, for emergency response, laboratory samples are often used to verify initial field readings.

To ensure that the air samples meet the needs of each situation, a *monitoring strategy* is developed to clearly answer questions such as:

- What is the reason for this monitoring?
- What jobs, tasks, or exposures should we monitor?
- What contaminants should we measure?
- What monitoring techniques should we use?
- How many samples should we collect?
- When should we monitor?
- Who will perform monitoring and laboratory analysis?
- How will the results be used and communicated?

It is also important to note that even very accurate air sampling may not reflect an individual's total exposure to a material if ingestion, skin absorption, or mucous membrane absorption contributes significantly to the overall exposure. Additionally, any periods where the individual wears respiratory protection must be accounted when evaluating the health implications of the exposure. These topics should be addressed in the *strategy*.

After the strategy is completed, a written *monitoring plan* is prepared to spell out the details of the monitoring, such as number and types of samples that will be collected. Both the strategy and plan are continually reviewed as initial samples are collected or more experience is gained, and both are modified to reflect the new information. See Chapter 3 for more details on the *monitoring strategy* and *plan*.

TYPES OF AIR MONITORING

There are three main types of air samples: personal, area, and source.

Personal Sample

These samples measure a particular individual's exposure to airborne contaminants. These measurements are performed using sampling devices that the person wears or that are otherwise positioned in the person's breathing zone as they go about their activities. Personal samples are usually collected for comparison with an exposure standard such as: a regulatory requirement; a recommendation from a consensus group, professional association, or government agency; or an internal standard adopted by the employer or other organization concerned with the exposure. Often the results of personal monitoring are considered to be representative of a larger population group than the people who were actually monitored, such as community residents or workers in the same job classification. Because the individual usually wears the sampling device, its weight and bulk are an important factor when selecting the sampling device. Typical sampling devices include either small battery-powered pumps with a suitable collection device (Figure 1.2), a passive sampler that relies on diffusion of the contaminant into the sampler where it is captured (Figure 1.3), or a small real-time direct reading instrument with a high-level alarm and data storage capability (Figure 1.4).

Area Sample

With this type of sample the contaminant levels are measured at a particular area, either continuously, periodically, or at a discrete point in time. This type of sampling is used where:

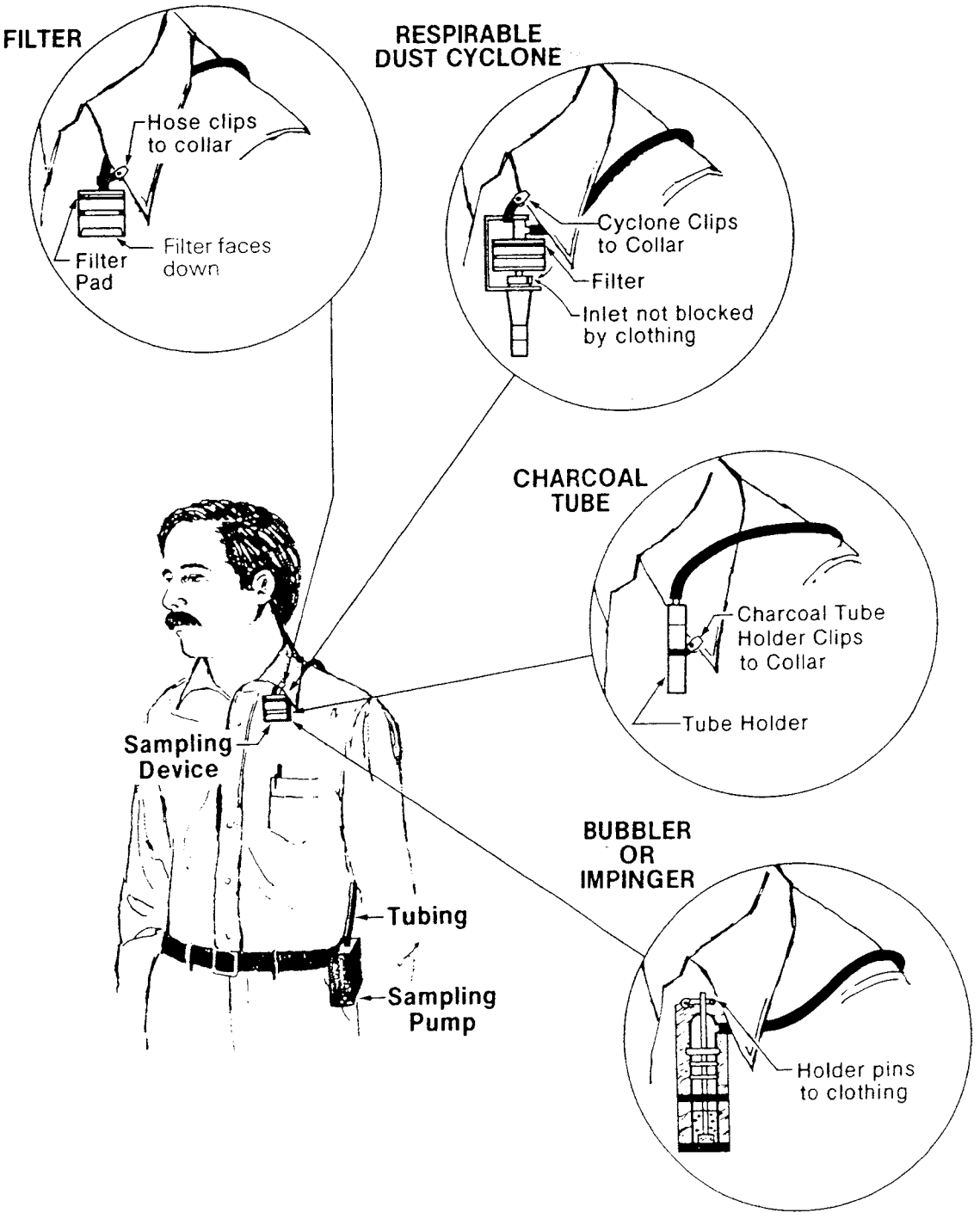

Figure 1.2. Breathing zone samples collected with a personal pump.

Figure 1.3. Passive dosimeter collects gases and vapors without a sampling pump. (Courtesy of SKC, Inc.)

Figure 1.4. Personal-size direct reading electronic instrument for air contaminants. (Courtesy of Industrial Scientific Corporation.)

- Suitable personal sampling (portable) techniques are not available, and so area measurements are the best surrogate for personal samples.
- A fixed direct reading system (often with multiple sensors or pickup points located throughout the area) that periodically or continuously measures airborne levels is advantageous for confirming that concentrations are low, as well as for identifying leaks or other causes of higher-than-expected levels. The sampling points must be near enough to likely leak or release locations so that high airborne levels in the area trigger warning alarms before people are overexposed.
- Portable survey instruments ("sniffers") are used to measure airborne levels before people are allowed to enter or remain in the area. These are often used for emergency releases and when people work in confined or enclosed areas.

Where the area sampler is a direct reading device, it is usually equipped with audible and/or visible alarms to warn of high levels.

Area samples are generally not a good way to estimate personal exposures because people normally move around and so are not continuously exposed to the concentration that exists at the fixed measuring location. The likelihood of underestimating actual exposures is obvious if an employee works nearer to the contaminant source than the sampling point is located. However, there are also many opportunities to overestimate exposures using area readings, so caution should always be used. If area samples are used to estimate personal exposure, it should be done as part of a detailed study where the location and movement pattern of the people are recorded along with the variables (such as production rate, release rate, amount spilled, etc.) that govern airborne levels.

Source Sample

These are samples collected directly at the contaminant source either to measure normal release rates or to immediately identify any leaks, releases, or control system malfunctions. These may appear to be similar to "area" samples, but are different in that they do not purport to reflect concentrations in the general work or occupied area. For example, some air pollution regulations require periodic "sniffing" using a direct reading device of pipe flanges, seals on rotating pumps, other locations where volatile organic compounds may be released, or other piping connections. Another application is where a laboratory hood containing flammable gases is equipped with a sensor and alarm device to warn of concentration buildup due to gas leaks or a malfunctioning ventilation fan. It is important to understand when source rather than area data are being collected since source values cannot be used to estimate personal exposures.

Integrated Versus Grab Samples

Air samples can be further categorized:

- *Integrated sample*—estimates exposure over a time period such as a work shift by collecting one or more personal samples that cover the entire time period. The term "integrated" means that the measured exposure level integrates or averages all of the different concentrations and time durations during the time period of interest. Community environmental standards may refer to a 24-hour exposure, while occupational exposure standards often specify the allowable integrated exposure over the work shift or other time period, which is called a *time-weighted average* (TWA) exposure level. Some exposure standards specify an allowable *short-term exposure limit* (STEL) measured over 15 minutes or so—in this case, one or more separate sample(s) would be collected to cover the 15-minute time period(s) of expected highest exposure. This 15-minute sample would also be referred to as an *integrated* sample since it covered the time period of interest (15 minutes).
- *Instantaneous or grab sample*—a sample collected over a very short time period, usually less than 5 minutes. These samples are used to evaluate a peak or "ceiling" (maximum) exposure. Some sampling devices can only collect this type of sample since they have a very short sampling time (such as a "hand pump and detector tube," described later). It is very difficult to estimate a full-shift personal exposure from a series of grab samples, although there are statistically based sampling strategies that can be applied. Typical uses of grab samples are: to determine maximum peak exposures; for range finding sampling to determine if an airborne contaminant is present as a precursor to more detailed monitoring; or for "go/no go" decisions following purging or ventilation of a work area.

AIR SAMPLING TECHNIQUES

There are two main categories of sampling techniques: (a) *sample collection devices* that are analyzed in a laboratory (b) and *direct reading instruments*. Both of these techniques have application with the major types of contaminants: gases, vapors, and particulate matter (aerosols):

- *Gas*—a material with very low density and viscosity and that readily and uniformly distributes itself throughout any container at normal temperature

TABLE 1.2. Air Monitoring Techniques

Sample Collection Device Sampling	Direct Reading Methods
Sample collection methods	Electronic instruments
Pump-based methods	Combustible gases
Passive methods	Specific gas or vapor
Laboratory analysis	Nonspecific gas and vapor
Chemical analysis	Particulate matter
Other analysis	Colorimetric systems
	Detector tubes
	Paper-tape or liquid devices
	Other colorimetric devices

and pressure. As used in this context, a gas is a material that exists in a gaseous state at normal ambient conditions. Concentrations of gases are expressed in mass of contaminant per unit volume of contaminated air (mg/m^3) or parts of contaminant per million parts of contaminated air (ppm) by volume.

- *Vapor*—the gaseous form of substances that are normally solid or liquid at room temperature and pressure. Vapors are generally formed when volatile liquids, such as solvents, evaporate. Concentrations of vapors are expressed in the same units as gases.
- *Particulate matter*—discrete units of fine solid or liquid matter, such as dust, fog, fume, mist, smoke, or sprays. Particulate matter suspended in air is commonly called an *aerosol.* Concentrations of particulate matter are generally expressed in mass of contaminant per unit volume of contaminated air (mg/m^3), although units such as fibers/cm^3 of air are used for asbestos and some other fibrous materials.

Table 1.2 shows how the specific monitoring techniques are categorized under these two main headings. Appendix D is a table listing the recommended sampling techniques for common contaminants. For air sampling considerations, gases and vapors often behave similarly and thus are discussed together below.

SAMPLE COLLECTION DEVICES

With this approach a sample is collected in the field and returned to a laboratory for analysis. The summary below focuses on air samples to determine an individual's personal exposure level; similar principles apply to sampling for environmental quality purposes except that the equipment is generally larger. To ensure accurate results, all aspects of sampling and analysis including type and size of sampling device, sampling rate and total sample volume, and sample storage and handling *must* follow the sampling procedure or protocol for the method and the material(s) being analyzed. Table 1.3 (from the *OSHA Benzene Standard*) is an excerpt of a typical air sampling procedure. It is especially important to discuss the sampling beforehand with the analytical laboratory so the sample will be collected and handled in a manner that permits accurate analysis once it reaches the laboratory. Factors to consider include:

TABLE 1.3. Summary of Sampling and Analytical Methods for Benzene

Methods for Benzene Monitoring
(Excerpt from OSHA Benzene Standard—Appendix D)

General:

- Measurements are best taken so that the representative average 8-hour exposure may be determined from a single 8-hour sample or two 4-hour samples.
- Short-time interval samples (or grab samples) may also be used to determine average exposure level if a minimum of five measurements are taken in a random manner over the 8-hour work shift. The arithmetic average of all such random samples taken on one work shift is an estimate of an employee's average level of exposure for that work shift.
- Air samples should be taken in the employee's breathing zone (air that would most nearly represent that inhaled by the employee). Sampling and analysis must be performed with procedures meeting the requirements of the standard.
- The employer has the obligation of selecting a monitoring method that meets the accuracy and precision requirements of the standard.
- The method of monitoring must have an accuracy, to a 95% confidence level, of not less than plus or minus 25% for concentrations of benzene greater than or equal to 0.5 ppm.

Methods:

- Collection of the benzene vapor on charcoal absorption tubes, desorption in the laboratory with carbon disulfide, and subsequent chemical analysis by gas chromatography (OSHA Method 12).
- Portable direct reading instruments, real-time continuous monitoring systems, passive dosimeters, or other suitable methods.

Overview of OSHA Method 12 for Air Samples:

- Recommended air volume and sampling rate when using standard charcoal tubes containing 100 mg of charcoal in the front section and 50 mg of charcoal in the backup section of the tube: 10-L sample collected at 0.2 L/min. Air sample size is limited by the number of milligrams that the tube will hold before overloading.
- When the sample value obtained for the backup section of the charcoal tube exceeds 25% of that found on the front section, the possibility of sample loss exists.
- The limit of detection for this analytical procedure is 1.28 ng with a coefficient of variation of 0.023 at this level. This would be equivalent to an air concentration of 0.04 ppm for a 10-L air sample.
- Field Sampling Considerations:
  - Calibration of personal pumps. Each pump must be calibrated with a representative charcoal tube in the line.
  - The charcoal tube should be placed in a vertical position during sampling to minimize channeling through the charcoal.
  - Air being sampled should not be passed through any hose or tubing before entering the charcoal tube.
  - A sample size of 10 L is recommended. Sample at a flow rate of approximately 0.2 L/min. The flow rate should be known with an accuracy of at least (+ or –) 5%.
  - The charcoal tubes should be capped with the supplied plastic caps immediately after sampling.
  - Submit at least one blank tube (a charcoal tube subjected to the same handling procedures, without having any air drawn through it) with each set of samples.
  - Take necessary shipping and packing precautions to minimize breakage of samples.
- Gas Chromatograph Parameters:
  - Use a flame ionization detector (FID).
  - Column: 10-ft × 1/8 -in stainless steel packed with 80/100 Supelcoport coated with 20% SP 2100, 0.1% CW 1500.
  - Operating Conditions: 30 mL/min (60 psig) helium carrier gas flow; 30 mL/min (40 psig) hydrogen gas flow to detector; 240 mL/min (40 psig) air flow to detector; 150°C injector temperature; 250°C detector temperature; 100°C column temperature; 1-μL injection size.

- Physical and chemical characteristics of the contaminant(s)
- Possible interferences to the collection or analysis
- Required accuracy and precision
- Type of sample (personal, area, source)
- Duration of sampling period

Pump-Based Sampling

The sampling arrangement consists of a calibrated battery-powered pump, collection device, and connecting tubing (Figure 1.2). Some procedures may also include an airflow control valve, an airflow measuring device, and a special particle size separator device (for some particulate matter sampling). The pump sampling rate is adjustable and is chosen to match the airflow requirements of the sampling procedure—often personal pumps are categorized as either "high flow" (1–10 L/min) or "low flow" (1–1000 cm^3/min). Some battery-powered sampling pumps can operate as either high- or low-flow pumps. Two different low-flow designs are available: (a) a stroke-volume (pulsating flow) pump that functions using a known-volume piston to move the air while a counter records the number of piston strokes and (b) a continuous-flow pump with an airflow rate indicator.

Before use, the pump is calibrated (see Chapter 5) so the airflow rate is known; after use, and periodically for a long-duration sample, the pump calibration is checked to ensure that it has not changed. Once the pump flow rate is determined, the volume of air sampled is calculated from either:

- Airflow rate (L/min) × sampling time (minutes) for a continuous-flow pump
- Stroke volume (cm^3/stroke) × number of pump strokes for a piston-type pump

Sampling using evacuated containers can be considered a modification of pump sampling (Figure 1.5). In this case a vacuum pump is used to produce a vacuum in a suitable container. The container may be plain stainless steel or have a specially treated interior surface for sampling reactive chemicals. Container size depends on sampling time; a 6-L volume usually is sufficient for a 24-hour sample. A valve on the container is opened to start sampling as ambient air is drawn into the container. A flow control orifice or other device is used to regulate the airflow into the container so that the flow rate is constant over the sampling period. The valve is closed at the end of the sampling period.

For all pump-driven sampling techniques, a key parameter to be decided is the sampling rate for the sample. The concepts of *limit of detection* and *limit of quantification* help determine the best sampling rate to use:

- Limit of detection (LOD) is the least amount of contaminant that can be "seen" by the analytic method even though the amount cannot be accurately determined.
- Limit of quantification (LOQ) is the minimum amount of contaminant that can be quantified with some specified degree of accuracy.

Analytical results below the LOD are reported as "<LOD (with the LOD specified)." Analytical results greater than the LOD but below the LOQ are reported as "detected, but not quantified (with the LOQ specified)." Some analytical methods (particularly older versions) may not specify a LOQ, but the LOD should always be specified in the written procedure.

The concept of LOQ is used to determine the minimum sampling volume needed for accurate analysis, which in turn determines the sampling rate. In order to perform this calculation, you must first

Figure 1.5. Evacuated cylinders collect samples at a controlled rate without use of a pump. They are available in a variety of sizes. (Courtesy of Galson Laboratories.)

decide the minimum airborne concentration that you need to quantify. Usually this is some percentage (often 10% or lower) of the allowable exposure limit.

$$\text{SV} = \frac{\text{LOQ}}{\text{EL} \times F}$$

where SV is the minimum sample volume (L), LOQ is the lower limit of quantification (μg), EL is the allowable exposure limit (mg/m^3), and F is the percent of EL that needs to be quantified.

Once the sample volume is determined, that value can be used to select the sampling rate and sampling time since

$$\text{SV(L)} = \text{Sampling rate (L/min)} \times \text{Sample time (min)}$$

In some cases the sampling time is fixed (e.g., for a 15-minute short-term exposure sample), and so the above equation is used to determine the sampling rate. In other situations the maximum sampling rate is dictated by the pump capacity and so the equation determines minimum sampling time. If the sampling method you are considering will not collect enough contaminant to accurately measure the minimum airborne level you are interested in, then it is necessary to look for another method.

For many sampling/analytical methods there is also a *maximum* amount of contaminant that can be quantified in a sample either because of overloading the collection device or other problems. Generally the sampling duration for each sample can be reduced to avoid this type of problem. For example, instead of collecting one 8-hour sample during the shift, it might be necessary to collect four 2-hour samples to cover the shift to avoid overloading the sample device. The time-weighted average concentration is then calculated to yield the average for the shift.

The specific sampling collection device depends on the material being sampled:

Gases and Vapors. For gases and vapors, typical collection devices include:

- Adsorption tubes (also called *sorbent tubes*) containing charcoal (activated carbon), silica gel, or another sorbent (Figure 1.6), depending on the contaminant. The tubes contain two sections of adsorbing material separated by an inert spacer. As contaminated air is drawn through the tube, the airborne chemical is adsorbed (deposited on

Figure 1.6. Charcoal adsorption tubes collect organic vapor for later laboratory analysis. (Courtesy of SKC, Inc.)

the surface) on the adsorbent particles in the front section. If the front section becomes saturated with the contaminant molecules, the remaining contaminant molecules "break through" the front layer and are collected on the backup section. At the laboratory, each section is analyzed separately; and if significant breakthrough has occurred, the results will be questionable and so the sampling should be repeated. A special *screening* adsorption tube is available that has several different adsorbent layers in a single tube. These are useful for initial sampling for unknown contaminants and in some indoor air quality investigations. Vendors can also provide custom-packed adsorption tubes to meet special sampling needs.

- Absorption devices such as a small vial with a bubbler fitting. The vial holds deionized water to absorb the airborne gas or vapor, or a dilute chemical reagent to react with the contaminant (Figure 1.7). These are used where adsorption tubes are not available, but the added steps of handling liquids in the field often make these techniques less desirable than an adsorption tube.
- Specially treated filters similar to those described below for particulate sampling which are used for monitoring certain reactive chemicals. The airborne chemicals react with the compounds are on the filter to form other chemical compounds that are stable and can be measured in the laboratory.
- Sampling bags made of Tedlar or Teflon can be used when the air concentration is above the LOD (and so the ambient air can be analyzed directly back in the laboratory). A sampling pump or other means is used to fill the bag with ambient air. Bags are rarely used when another sample collection method is feasible due to the bulk of the bag, shipping limitations, and the possibility of sample degradation prior to analysis.

Figure 1.7. Midget impingers collect air contaminants in a liquid for later laboratory analysis. (Courtesy of SKC, Inc.)

Particulate Matter. For particulate matter, high-flow pumps along with these sampling devices are most commonly used:

TABLE 1.4. Typical Air Sampling Filter Materials

Filter Material	Characteristics	Typical Applications
Glass fiber	High particulate retention and wet strength	Gravimetric analysis
Polyvinylchloride (PVC)	Low tare weight	Gravimetric analysis
Mixed cellulose ester (MCE)	Dissolves easily	Metals and fibers
Gelatin	High moisture content, can be pre-sterilized	Airborne microbes
Teflon	Strong and chemically resistant	Acids, bases, and solvents
Polycarbonate	Glass-like surface, transparent and straight-through pores	Gravimetric and microscopic analyses

Source: Reference 3.

- *Filters.* Different filter materials are available, depending on the contaminant being sampled; Table 1.4 lists a few common filter materials. Since sampling with the incorrect filter often makes analysis impossible, it is critical for the sampling practitioner to coordinate with the laboratory to ensure that the proper filter is used for each type of air sample. The usual filter is 37 mm in diameter, enclosed in a filter cassette unit attached to the pump. The cassette has a small hole for the air being sampled to enter, which avoids deposition of larger particles in the ambient air onto the filter. The filter by itself is used to collect total particulate samples, which may include particles too large to actually reach or be deposited in the human respiratory system when inhaled. Various-size separators are used to collect only those particles within the size distribution of interest. For example, a small "cyclone"-size separator can be mounted before the filter to separate and discard particulates that are larger than an established "respirable size" distribution. Asbestos samples are collected on 25-mm-diameter mixed cellulose ester (MCE) filter in an electrically conductive cassette to avoid fiber loss due to electrostatic effects. Asbestos sampling is performed with the full filter face open to the ambient air in order to get an even distribution of fibers across the filter since the analytic techniques involves optical counting of the fibers.
- *Inertial Impactors.* These retain particulates due to impaction as the airflow hits a "collecting" surface. The collection efficiency is determined by the mass of the particulate, the characteristics of the collecting surface, and the velocity of the air stream. Inertial impactors with several "stages" can be used to obtain a size distribution of the particulate matter (Figure 1.8). The

Figure 1.8. Six-stage inertial impactor for particulates. (Courtesy of Thermo Electron Corporation.)

stages can be weighed after sampling to determine the mass of contaminant retained, or they can be analyzed using chemical methods. For bioaerosol sampling, agar plates or other suitable growth media are used as the collecting surfaces.

- *Impingers.* These capture particles in a liquid (usually water) after being drawn at high velocity into a liquid-filled vial (Figure 1.7). The particles impinge on the vial bottom, then lose their velocity and are trapped in the liquid. A sample of the liquid is counted in a special cell under a microscope to determine particle count and size distribution. These devices are generally used if a filter or other suitable technique is available.

Passive Sampling

With this technique no pump or other air moving device is used—the contaminant diffuses at a predictable rate according to a scientific principle called Fick's Law. The contaminant molecules move from the area of higher concentration (the ambient atmosphere) to the zone of lower concentration (inside the collection device) where they are trapped for later analysis.

Gases and Vapors. A passive monitor for gases and vapors is typically a small badge-like device that clips to the person's collar or can be mounted for fixed area samples (Figure 1.3). Other devices resemble small glass vials. These devices consist of a protective membrane covering the opening and a collection medium pad or matrix inside the device. The collection medium (such as charcoal) for any contaminant is generally the same as used in the adsorption tubes described above, and the laboratory analysis is similar. Some devices have two collection stages: the main collector plus a backup that will indicate if the main collector pad was saturated or overloaded during air monitoring. Passive monitors are available to monitor for over 200 substances.

The "sampling rate" for any passive device for a specific contaminant is determined by the "diffusion coefficient" of the chemical and also by the diffusion path or distance based on the internal dimensions of the device. The effective sampling rate is provided by the device's manufacturer.

Sample collection occurs as long as the monitor is exposed to the atmosphere, and it continues until the device is resealed. Depending on the design of the particular device, they are provided in a protective package or with a protective cover over the front membrane. The start and end times are recorded and used to calculate equivalent sample volume. For accurate measurements the devices need a certain minimum airflow across the membrane to ensure that the air layer at the membrane represents the ambient atmosphere. Normal worker motions are sufficient to produce the needed velocity, and for fixed badges normal air currents should suffice. If the devices are mounted in stagnant locations, a room fan or other similar method of generating air movement may be required.

The major advantage of passive sampling compared to pump-driven monitoring is the simplicity of not having to deal with a pump with the attendant pump calibration, maintenance, and power (battery charging or line power supply) issues. For short-term samples at low contaminant levels the limit of quantification may become an obstacle for some passive devices. The unit cost of passive monitors is greater than the cost of comparable adsorption tubes, but the overall cost (when the pump and people's time is included) is generally lower for passive sampling. Note that there are also direct reading passive dosimeters; these are discussed later under the "Colorimetric Systems" heading later in this chapter.

Particulate Matter. For particulate matter samples collected for laboratory analysis, passive monitors do not compete with pump-driven sampling as they do for gas and vapor sampling. Settled dust samples can be collected on an open Petri dish or similar surface for chemical identification, or on nutrient plates to culture airborne bioaerosols. However, passive measurements cannot be used to determine breathing zone concentrations of particulate matter in mg/m^3, $fibers/cm^3$, or similar concentration units.

Laboratory Analysis of Samples

When performing monitoring with the *sample collection devices* described above, the samples are sent to a laboratory for analysis of the collected material. This section provides a brief overview of the various analytical techniques. Often the person collecting the samples is not directly involved with their analysis, and they may view the laboratory analysis as a function too detailed or complex to get involved with as long as the results are timely and accurate. This is understandable, but the likelihood of valid sample results is increased if the sampling practitioner has at least a general understanding of the laboratory methods and possible interferences for their samples. In every case it is important to consult with laboratory specialists *before* the samples are collected in order to ensure that the laboratory will be able to analyze the samples for the contaminants of interest in the concentrations anticipated and with any possible interference from other airborne compounds.

Although there are a variety of analytical techniques used for air sample analysis, a key function of every laboratory is quality assurance. This is the process of following the appropriate method, performing equipment calibration, analyzing reagents for interferences, determining sample recovery from the collection device, evaluating shelf life of samples, running analytical blanks, performing duplicate analysis on split samples, and training and evaluating staff that helps ensure that the results are accurate and reproducible. "Pre-spiked" adsorbent tubes and passive dosimeters can be purchased to assist in the quality assurance effort. These are usually "loaded" with the contaminant of interest to represent half of the allowable exposure level, and they are submitted to the laboratory along with field samples. A good indication of strong quality control is when the laboratory has achieved accreditation by a recognized body. The Industrial Hygiene Laboratory Accreditation Program administered by the American Industrial Hygiene Association is a leading example of an accreditation program.[4] Similar programs are also available from other organizations.

Chemical Analytical Techniques. These techniques identify the mass or amount of a chemical compound or class of compounds in a sample. There is some overlap between the chemical analysis techniques used for gases, vapors, and particulate matter, so they are covered together:

Gas chromatography (GC) is commonly used for gases, organic vapors such as solvents or alcohols, and some compounds that are solids at room temperature but can be volatized sufficiently at 225°C. It operates on the principle that a volatilized sample is mixed with a carrier gas and injected into a column that separates the components in the sample according to the time it takes the component to travel through the column (Figure 1.9). As the molecules emerge from the column, a detector measures the amount of each material. On a chromatogram, each emerging compound is represented by a "peak" based on its elution time. Component identification is made using a data "library" developed by injecting samples of known chemicals into the column and measuring the travel time for each. The concentration

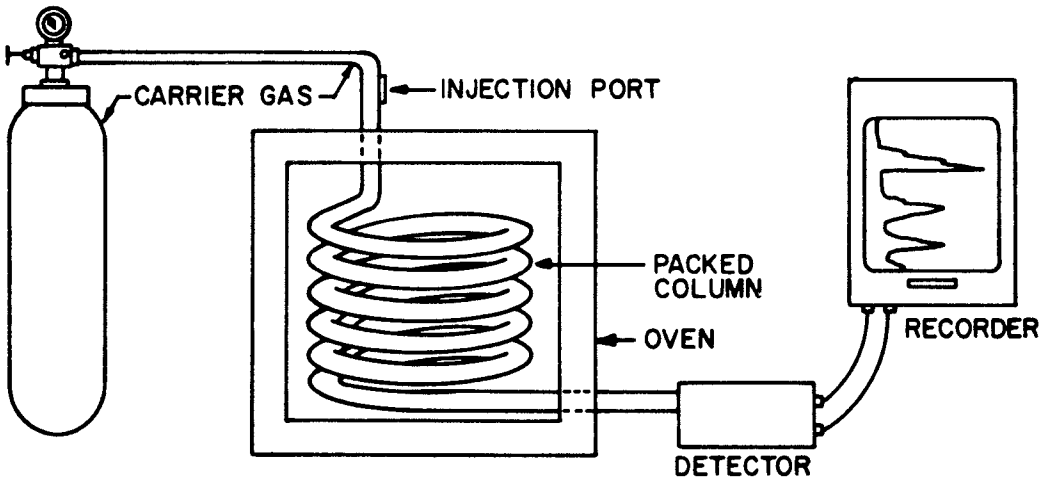

Figure 1.9. Diagram of a typical gas chromatograph. (From *The Industrial Environment—Its Evaluation and Control*, NIOSH, Washington, D.C., 1973.)

of each material is represented by the area under its peak on the chromatogram.

The GC's ability to identify many different chemicals, especially those in mixtures, is achieved through proper selection of column, detector, and temperature programming. The ideal situation is to choose the operating parameters to yield sharp and narrow peaks that are easy to identify and quantitate for the materials of interest:

- There are two types of columns: packed and capillary. The packed column, typically 1/8 inch in diameter and up to 20 feet long, contains an inert solid support that is coated with a liquid material. The capillary column is a very narrow tube (<1 mm in diameter) with a coating on the wall of the column, which may be over 100 m long. The function of the column geometry and coating is to control the movement of sample molecules so the optimum separation is achieved for the materials of interest as they emerge from the column.
- Different detectors are used to measure the materials as they emerge from the column. The most widely used is the flame ionization detector (FID) that functions by burning the sample in a hydrogen flame and measuring the current produced by the ionized material. Organic materials like hydrocarbons that burn have a much greater response than materials that do not burn. Other common detectors include (a) the electron capture (EC) detector used to measure chlorinated pesticides, PCBs, and other halogenated materials and (b) the thermal conductivity detector (TCD) that responds to gases like oxygen and nitrogen as well as organic compounds. The GC/mass spectrometer (GC/MS) is a special detector that passes the ionized molecules emerging from the column through an electric field that focuses the molecules by atomic mass. This permits identification of specific compounds using a library of data developed for the specific instrument.
- Temperature programming involves increasing the temperature of the column in a predetermined manner as

the analysis proceeds. This enhances separation of many complex mixtures because the lower-molecular-weight compounds move through the column at the lower temperature, while heavier molecules begin to move more quickly as the column temperature is increased.

The most common air sampling application is use of a charcoal sorbent tube for field air sampling, such as for benzene (see Table 1.3). The GC column, detector, and temperature program are selected as specified in the analytical procedure for the compound(s) being measured. The GC instrument is set up and tested using quality assurance steps, which may include (a) checking the solvents and other reagents for interferences and (b) calibrating the instrument using known concentrations of the contaminant being measured. In the laboratory, the actual field sample tubes and one or more "field blank" tubes are handled the same way: The main and backup sections of charcoal are removed from the tube and placed in separate vials. A small quantity of solvent is added to each vial and the contents agitated to desorb the captured contaminant. A portion of the solvent/contaminant sample is injected into the GC, and the analytical cycle is initiated. The GC runs through the temperature program, and the peak area on the chromatogram for each contaminant is analyzed by computer to yield the amount of that contaminant in the sample. If the backup section of the sample contains more than 25% of the amount on the front section, the possibility of sample loss due to breakthrough in the field is noted on the analytical report. If needed, the analytical results can be adjusted to account for any contaminant that was not desorbed by the solvent based on desorption efficiency tests. Because only a portion of the solvent/contaminant sample was injected into the GC, the run can be repeated to check reproducibility or if there were any instrument problems during the first test. Sometimes the analysis is repeated on one or more instruments using different test conditions in order to measure all contaminants of interest.

Another desorption technique is *thermal desorption*, where the adsorption tube is heated and the collected contaminants are "blown" off the tube with the carrier gas into the GC column. This technique can achieve a lower LOQ than the solvent desorption method since the entire sample (rather than a small portion) is analyzed. However, since the entire sample is analyzed, the GC run cannot be repeated with the same sample if there are any analytical problems.

High-pressure liquid chromatography (HPLC) is a technique that may be used for compounds unsuitable for GC analysis because they are thermally unstable or not volatile enough. HPLC uses a column to separate compounds, but the carrier material is a liquid rather than a gas. To enhance separation, the composition of the carrier solvent may be changed as the analysis progresses, similar to the temperature increased used with GC to improve separation. The detector for HPLC must be suitable for measuring the compounds of interest in a liquid and may be based on principles of electrochemical detection, refractive index, ultraviolet or visible light absorption, or fluorescence.

Infrared spectroscopy is a technique that uses an optical instrument that measures the absorption of "light" in the infrared spectrum by the sample. It can be used for solids, liquids, and gases. The general principles of operation are described in Chapter 12 on direct reading instruments.

Atomic absorption spectrophotometry (AA) is used for analyzing air samples (often collected on filters) for metals. The technique involves dissolving a portion of the sample filter in an acid, and then atomizing this solution in a flame and measuring

the how much light at one or more specific wavelength(s) that the flame absorbs. The light source usually is made with a cathode made from the metal being analyzed for, which emits a spectrum of that element. AA is highly specific and has few interferences, and it routinely used for over 50 metals including lead, mercury, chromium, arsenic, copper, zinc, cadmium, nickel, beryllium, and others of occupational health or environmental concern.

Ultraviolet-visible spectroscopy (UV-VIS), or wet chemistry, is based on the absorption of light by a colored compound where the absorption is proportional to the concentration of the material. It can be used for molecules that absorb either UV or visible light, or where the molecule can be reacted to form another compound that does. UV-VIS is generally less sensitive and less specific than the techniques discussed above; in particular, UV-VIS is subject to more interferences. For some materials, UV-VIS is preferred because it will distinguish between different oxidation states of the material. For example, UV-VIS will identify Cr^{6+} (i.e., hexavalent chromium) from total chromium, which is useful because Cr^{6+} is a recognized human carcinogen.

X-ray diffraction (XRD) and similar tests are based on the principle that a beam of X rays is affected by crystals in compounds in such a way that the amount of the material can be measured. It is used to determine the amount of free crystalline silica (i.e., quartz, cristobalite, and tridyimite) in air, settled dust, or bulk samples.

Other (Nonchemical) Analytical Techniques. *Gravimetric analysis* means that the filter or other sample collector is weighed to determine the amount of particulate matter collected. This is a nonspecific technique: All material on the filter is included even if it is not the contaminant of interest. While most contaminants are now determined using other analytical methods that give the quantity of the compound in the air sample, materials such as wood dust, coal dust (<5% silica), metal working fluid mist, cotton, and grain dust are still measured gravimetrically. There are two main approaches to gravimetric analysis:

- Weighing the filter before sampling (determining the *tare weight*) and then reweighing it after sampling. Generally the filter has to be desiccated (dried) in a controlled manner before each weighing to avoid error from moisture on the filter.
- Use of stacked, matched weight filters. Using this technique, the manufacturer places (or *stacks*) two filters weighing the same in a single sampling cassette. The particulates are retained on the first filter during sampling, and the weight of the second filter is unchanged. At the laboratory, each filter is weighed separately; the amount of matter collected equals the difference in weight between the two filters.

Microscopy involves counting the number of particles or fibers with some type of microscope. One technique for counting asbestos fibers is to dissolve part of the filter with a solvent and then count certain fibers using phase contrast microscopy (PCM) according to a rigorous counting methodology (Figure 1.10). Since this techniques counts all fibers, in a "mixed" fiber environment it will tend to overstate the amount of asbestos. In these cases, scanning electron microscopy (SEM) or transmission electron microscopy (TEM) are two techniques that can identify and count only the asbestos fibers. Microscopy is also used for bioaerosols as described below.

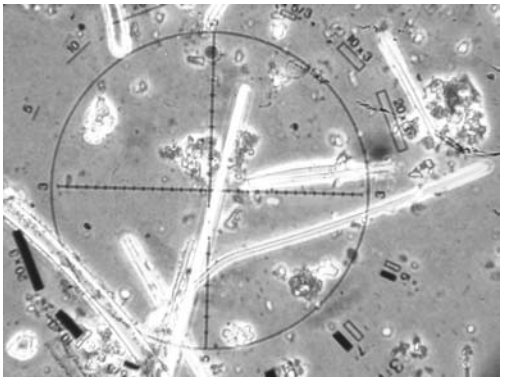

Figure 1.10. Asbestos fibers under phase contrast microscopy. (Courtesy of Forensic Analytical.)

Ionizing radiation concentration or activity is generally determined by performing standard counting techniques on filters or other collection devices. Radon (a gas) is determined by collecting the gas in a charcoal canister or by counting the alpha tracks caused by its decay on a sample of special polymer material.

Bioaerosols—the technology of identifying and quantifying bacteria, fungi, and viruses in air samples has progressed rapidly in recent years, primarily due to increased concern about indoor air quality and mold problems. Still there are few accepted standards for this type of analysis, and so close contact with the analytical laboratory is needed when first considering a bioaerosol sampling project. Often the laboratory provides the bioaerosol collection media that is suited to their analytical methods rather than the sample practitioner using off-the-shelf air sample collection devices. Common analytical methods, in addition to specific identification of toxic agents, include counting colonies that grow on nutrient plates, counting fungal spores using microscopy techniques, and determining the amount of endotoxin (a portion of the cell wall of gram-negative bacteria) using chemical or biological methods.

Understanding Laboratory Reports

With practically all of the air sampling devices and analytical techniques described above, the laboratory determines the *amount* of the contaminant(s) in the sample. This is expressed in weight or mass units such as milligrams (mg) or micrograms (μg). For optical counting techniques the report will indicate the number of fibers or colonies in the sample according to the counting protocol used.

In order to calculate the airborne concentration of the contaminants, it is necessary to divide the amount of contaminant by the volume of air that the sample represents. This is the reason for careful calibration of the sampling pump, scrupulous attention to pump start and stop times during sampling, and periodic checks of pump performance during the actual field sampling.

$$\text{Airborne concentration } (\text{mg}/\text{m}^3) = \frac{\text{Laboratory result (mg of contaminant)}}{\text{Air sample volume } (\text{m}^3)}$$

The unit mg/m^3 applies to the concentration of gases, vapors, and particulate matter (except for fibers or colonies that are counted). However, the allowable exposure level for some gases and vapors is expressed as "parts of contaminant per million parts of contaminated air" by volume (ppm). Use this equation to convert mg/m^3 to ppm:

$$\text{Concentration (ppm)} = \frac{\text{Concentration } (\text{mg}/\text{m}^3) \times 24.45}{\text{Molecular weight of contaminant}}$$

If only one air sample was collected to cover the entire exposure period, then the calculated air concentration for the sample represents the average concentration for the period (called the *time-weighted average*). However, if two or more sequen-

tial samples were collected (one after the other) rather than a single sample to cover the exposure period, the TWA is calculated from this equation:

$$\text{TWA} = \frac{(\text{Conc}_1)(\text{Time}_1) + (\text{Conc}_2)(\text{Time}_2) + \cdots + (\text{Conc}_{\text{last}})(\text{Time}_{\text{last}})}{\text{Exposure period}}$$

where TWA is the time-weighted average exposure for the period, Conc is the concentration in each sample, Time is the time period that each sample covers, and Exposure period is the total exposure period. In this equation the subscript ($_{1,2,\text{last}}$) refers to each sample collected sequentially to cover the time period. Also, for occupational exposures, "8 hours" (or 480 minutes) is generally used as the exposure period even if the work shift or exposure period was longer since the occupational exposure limits are based on an 8-hour workday. More details on this concept and the calculations are in Chapter 5.

DIRECT-READING DEVICES

The airborne concentration of many gases, vapors, and particulates can be measured in the field using direct-reading devices, thereby eliminating the time delay and effort of sending field samples to a laboratory for analysis. Most direct-reading devices are electronic instruments, although there are some where concentration is indicated by color change (called *colorimetric devices*). Direct-reading devices vary in purchase and operating cost, so cost comparison between direct-reading and laboratory sample approaches should be evaluated if appropriate. This chapter only gives an overview of the subject; Chapters 9–14 give details about the different types of direct-reading devices. The discussion below first covers electronic instruments and then colorimetric devices.

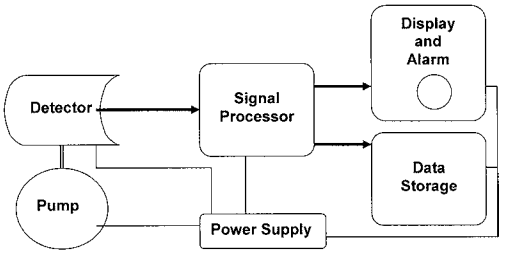

Figure 1.11. Diagram showing components of typical electronic direct reading instrument.

Electronic Direct Reading Instruments

Figure 1.11 shows a generic diagram of a typical direct-reading electronic instrument for gas, vapor, or particulate matter consisting of a detector, pump, signal processing unit, data display, power supply, and perhaps a data storage section. Of course all of these can be included in one small package—sometimes small enough to fit into a shirt pocket—but it is easier to understand the explanation of the different instrument types and capabilities in this section using this simple model. An ideal direct reading instrument is rugged, lightweight, easy to calibrate, and simple to operate, can operate over the temperature and humidity range it will be used in, functions for a long period without requiring maintenance, and, if battery-powered, has a long battery service life between charging. Typical components are:

- *Detector*—senses or measures the contaminant in the air. A pump may be used to drawn ambient air into the detector, although some devices rely on diffusion. The idea sensor is specific to the contaminant being measured, not responsive to potential interferences, not subject to fouling, is able to react quickly to changes in concentration, features a long service life before replacement is needed, and is inexpensive and easy to replace. The

sensor is often the most important selection criteria when choosing between direct reading instruments for a specific application.

- *Signal processor*—the electronic circuitry that takes the signal from the sensor and converts it into the concentration reading. Advances in microchip technology have allowed manufacturers to add more features and make this part of the instrument smaller and more powerful. This has allowed some instruments, such as infrared devices, to store a large library of infrared spectra from different materials that can be used in compound identification. A possible downside of the technical advances is that some devices have a lot of flexibility but a very small keyboard and readout screen—as a result considerable scrolling through menus is required to set up and use the instrument. This added complexity of operation can be a major problem for the occasional user since they do not use the instrument enough to become proficient.
- *Data storage*—many instruments can store a large number of individual readings collected at a preset interval in one second or less to several hours and then integrate these readings to give a time-weighted average value for all or part of the sampling period. Often the peak value is stored and can be displayed at a later time. Some devices store the individual reading that are collected throughout the sampling period so the data can be downloaded to a computer for further analysis and permanent storage. This data storage feature is also referred to as data logging. Separate, stand-alone data loggers may be used with some direct-reading instruments without their own internal storage capability.
- *Data display* shows the concentration levels and other information such as sampling time. The display can be a meter device or a digital readout. Often a meter will have multiple scales, so it is important that the user know which scale is in use at any time. For complex instruments with a digital display (especially with a small display), considerable scrolling may be required in order to read all of the data values. The instrument may also have audible or visual alarms if an established concentration is exceeded or if the instrument fails.
- *Power supply*—rechargeable batteries are a requirement for portable instruments. For these devices the operating life between charges is critical, and the charging period is also important. Portable instruments may often be used for long periods with the charger plugged into line current to allow sampling periods longer than the battery life. Fixed instruments generally operate on line power.

Recent advances in microchip and sensor technology have resulted in dramatic improvements in direct reading instruments. They are more sensitive, more accurate, more specific, smaller, and lighter and exhibit longer battery life than just a few years ago. They also have extensive data-logging capability. The improvements permit devices that were once barely portable to be conveniently used in the field, and also allow manufacturers to combine several sensor devices in a single instrument for measuring several contaminants. Personal size devices with datalogging can often be used in place of sample-pump methods requiring laboratory analysis. Since the technology is constantly changing, consult manufacturers' literature when considering direct reading devices for airborne contaminants.

A method of field calibration or at least "calibration check" is an important feature for any direct reading instrument. This is a means of exposing the sensor to a known concentration of contaminant in the concentration range of interest and then confirming that the instrument is measuring the proper level. Without this assurance, it is difficult to rely on the readings from these devices. Often the calibration system is a cylinder of a compressed gas containing the appropriate level of contaminant that is used to fill a plastic bag for calibration, or a small glass vial containing the compound that can be broken inside a test chamber to generate a known concentration. Availability of a suitable calibration check system can be a limiting factor for some applications of direct reading instruments; for example, gas mixtures may not be stable over time and generally the calibration system cannot be transported by common carrier to field sites without special shipping documents and procedures. A "check" button on the instrument that tests the electrical circuitry is *not* an adequate substitute for a calibration check using the challenge contaminant at the sensor.

Types of Electronic Direct-Reading Instruments

Combustible Gas Monitors. These instruments read the "percent of lower explosive limit" (LEL) of a flammable gas in air and have been a mainstay of firefighters, gas utility company personnel, and safety inspectors for many years. They function using one of these operating principles: the change in electrical resistance or thermal conductivity of a sensor as the flammables are oxidized in a chamber within the instrument; or a change in electrical conductivity of a metallic oxide sensor when flammable compounds are adsorbed on its surface. Proper calibration and use of these instruments are critical because they are used to identify potentially flammable or explosive atmospheres. Key parameter to understand when selecting and using an instrument include:

- How the instrument reacts when either in a flammable/explosive atmosphere or an oxygen deficient atmosphere. The meter on some devices may "peg out" on the high end and then drop to or below zero in an atmosphere that is above the upper explosive limit (UEL). Some will not function without adequate oxygen, which can be misread as a low LEL reading.
- The difference in response between the gas used to calibrate the instrument versus the flammable gas or vapor in the atmosphere. All of these devices are calibrated by the user using a known gas source. These instruments typically react based on the heat energy in the gas, and therefore they will show different readings when encountering gases with different heat values from the calibration gas. To ensure safety, a calibration gas should be used that will cause the percent LEL of other common gases to be overestimated rather than underestimated. For this reason, either pentane or hexane are often used for calibration, since with either of these two calibrating gases the level of other common gases and vapors will be overestimated. Conversely, methane would be a poor choice as a calibration gas because it can cause underestimation of the hazard from other gases (Table 1.5).
- Whether there are any compounds that will interfere with accurate readings or that can damage the instrument. Some compounds in high enough concentrations will impede the combustion of the flammable vapors at the sensor. Other compounds may

TABLE 1.5. Choice of Calibration Gas Is Critical for Safety

	Actual Concentration in Air of "Gas Being Sampled" when Meter Reads "100% LEL"	
Gas Being Sampled	with Hexane Calibration	with Methane Calibration
Acetone	70% LEL	170% LEL
Benzene	70% LEL	190% LEL
Ethylene	60% LEL	130% LEL
Methane	40% LEL	100% LEL
Methanol	50% LEL	110% LEL
Toluene	90% LEL	210% LEL

either overheat the sensor or coat it so it does not operate properly. Some devices use a "catalyst" to permit combustion to occur at a lower temperature; these may be subject to poisoning by certain compounds. An understanding of other airborne materials that may be present will aid in equipment selection and proper operation.

Instruments for Specific Gases and Vapors

ELECTROCHEMICAL OR METAL OXIDE SEMICONDUCTOR DEVICES. There are many instruments with sensors that detect a single or multiple specific compounds (Figure 1.4). Generally these have either electrochemical or metal oxide semiconductor detectors. In some devices, each sensor is specific for a single compound, so a device that measures multiple compounds has several sensors, while in other devices a single sensor can measure different gases, depending on sensor voltage and other operating parameters. A *simplified* explanation of each sensor is:

- *Electrochemical*—the sensor has two electrodes in a chemical matrix. The composition of the electrodes and matrix is chosen to sense the compound of interest, which is usually oxygen or a contaminant. When the compound contacts the chemical matrix, a reaction occurs that changes either the current or voltage between the electrodes (depending on the instrument). The change in current or voltage is proportional to the amount of the compound. In order to improve sensitivity and specificity, the sensor may feature a membrane that excludes interfering compounds from reaching the matrix, a catalyst that causes the reaction to proceed at a lower temperature, or a reference electrode to allow more accurate measurement of the current. If the reaction is sensitive to ambient temperature, a temperature sensor may be part of the circuitry to adjust the reading for fluctuations in ambient temperature.
- *Metal oxide*—the sensor consists of a semiconductor with a coating of a metallic oxide such as zinc, nickel or tin. As oxygen in normal air is adsorbed onto the coating, a baseline current flow develops in the semiconductor. When the oxygen is displaced by molecules of the contaminant, a change in resistance of the semiconductor occurs which is proportional to contaminant concentration. Selectivity is achieved through different mixtures of oxides and different operating temperatures. Some devices can measure several contaminants by modifying the