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ASSESSMENT OF INDOOR AIR QUALITY

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Environmental monitoring is conducted for a variety of purposes, including determination of compliance and enforcement, detection and diagnosis of unusual conditions, and research. The particular purpose of the investigation determines the contaminants to be sampled, the sampling locations, the instrumentation used, the frequency of measurements, and the required sensitivity of detection. This chapter begins by providing a systematic approach to investigating buildings. It focuses primarily on buildings whose occupants have experienced complaints potentially related to conditions in the indoor environment. The chapter then discusses air sampling equipment for measuring concentrations of gases and of particulate matter. The review is not comprehensive but illustrates the current options for assessing indoor air quality. More detailed descriptions of sampling strategies, methods, and equipment are available in recent books (Lioy and Lioy 1983; Nagda, Rector, and Koontz 1987; Lodge 1989; American Conference of Governmental and Industrial Hygienists [ACGIH] 1989). Chapter 3 addresses the dynamics of air exchange in homes and buildings and describes the commonly used methods for measuring airflow within buildings and the air exchange rates with outside air.

The growing recognition of indoor air quality problems in both homes and buildings has prompted the development of strategies for investigating these problems and for measuring indoor air quality. Investigations of indoor air quality problems may include engineering tests, physical or chemical measurements, health and comfort surveys of the occupants, and medical evaluation tests of the occupants (Lioy and Lioy 1983; Thorsen and Molhave 1987; Woods, Morey, and Rask 1987; Quinlan et al. 1989; Wallingford and Carpenter 1986). Typically, investigations are initiated (a) to demonstrate compliance with federal or state regulations; (b) to respond to complaints of poor air quality by building occupants; (c) to audit the space before occupancy, change of use of the space, or design modifications that may vary the physical layout; and (d) to evaluate the operating performance of systems. At present, complaints by occupants lead to the initiation of most investigations.

Occupants of buildings receive a large number of sensory stimuli that determine perceptions of the indoor environment (Baker 1989) (see Chapter 1). Each occupant integrates the many physical, chemical, and psychological inputs that together determine subjective judgment of the acceptability of the space. In achieving an acceptable indoor environment, those involved in the construction and subsequent operation of buildings must understand the complex nature not only of the structure and its operation but also of occupant responses. In addressing indoor air quality problems, investigators must also understand the complex interface between the occupants and the building environment.

Thus, many factors can cause complaints to be initiated by occupants, and a multidisciplinary approach, often involving building engineers, health professionals, and experts in indoor air quality assessment, is needed in investigating occupant complaints. A systematic approach should be taken to integrate the efforts of the team in order to resolve "problem buildings." Typically, a building survey includes four types of activity: communication, engineering analysis, instrumental surveys, and quality assurance. This chapter will discuss these aspects of building investigations and provide a condensed summary of some available instruments. Persons suspecting that their illness may be related to the building they occupy should be encouraged to undergo evaluation by appropriate medical personnel.

As environmental problems in buildings were initially recognized during the 1970s and early 1980s, traditional industrial hygiene measurement techniques were employed to evaluate indoor air quality. However, these methods generally do not have sufficient sensitivity to measure accurately the contaminant levels that are encountered indoors. To evaluate the indoor environment effectively requires a different perspective from that of traditional industrial hygiene. Regulatory compliance in the industrial environment is generally based upon meeting specific limits of individual exposures, that is, permissible exposure limits (PEL) (Occupational Safety and Health Administration [OSHA] 1989). Industrial hygiene surveys are directed at improved contaminant control or maintaining worker protection. Acceptable indoor air quality, on the other hand, is generally achieved through reliance on prescriptive criteria (e.g., outdoor air ventilation rates) to limit contaminant levels (American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE] 1989). These criteria, developed primarily for design purposes, recognize the numerous, nonspecific sources that may impact the indoor environment. New approaches designed for assessing the indoor environment are needed to investigate problem buildings, since the conventional industrial hygiene approach is not suitable (Woods, Morey, and Stolwijk 1988).

DESCRIBING THE PROBLEM: THE FIRST STAGE OF INVESTIGATION

The first step in conducting an investigation is to describe the scope of the problem; this first step often sets the tone for the entire assessment. An outside investigator may have difficulty in describing the full scope of the problem, however, because building occupants, management, owners, and facility operators often do not share a common level of concern. The responsibilities of these groups are different, and the actual or perceived consequences of the problem may vary among them. The threat of litigation may also impact decisions. However, the information gathered by the investigator at this time must be sufficient to describe the characteristics of the problem and to develop hypotheses concerning its source (National Institute for Occupational Safety and Health [NIOSH] 1987). This first stage might consist of a detailed walk-through survey of the building; a screening questionnaire for the occupants of the space; and interviews with management, employees, and other concerned parties such as involved medical and facilities personnel and industrial hygienists.

The health and comfort effects of concern should be described in this first stage. The populations at risk should be characterized by location, employment status, age, gender, or other potentially important attributes. Table 4.1 provides a brief guide for characterizing complaints; the description should cover the symptoms, the timing of occurrence in relation to entering and leaving the workplace, the severity, and the locations of affected persons. This information may provide links to changes in the operation of the heating, ventilating, and air-conditioning (HVAC) systems, to renovations, relocations, and equipment use, and to other factors.

Table 4.1 Initial Characterization of Complaints

Nature of complaints/symptom
Site or organ system affected (e.g., respiratory)
Severity
Duration
Associations
Treatment/confirmations
Timing of complaints
Long-term (continuing, periodic, seasonal, weekly, daily)
Short-term (isolated events)
Location of affected and not-affected groups
Numbers affected
Demographics of occupants with and without complaints
Age
Gender
Employment status

Table 4.2 Survey of Facilities

Physical layout of building
Work stations
Location of air supplies and returns
HVAC zones
HVAC inspection
Coils
Filters
Fans
Drip pans
Condensers
Air intakes
Distribution ductwork
HVAC operation
Load analysis
Control analysis
Assessment of modifications

Table 4.3 Potential Sources Impacting Air Quality

Exterior sources impacting air intakes
Loading docks
Roadways
Cooling towers
Other external sources
Locations of intake and exhaust vents
Interior sources
Insulation (man-made fibers, asbestos)
Equipment
Cleaning compounds
Office furnishings
Areas damaged by floods, high humidity, or other agents

During this initial survey, potential sources of contaminants in the space should also be identified. This characterization should assess whether the contaminants are continuously or intermittently present; whether specific point sources or area releases contaminate individual spaces; and whether the sources originate indoors or outdoors.

Finally, a history of the building should be developed. The history of the building mechanical system and its functioning should be reviewed, as should records of construction/renovation and building occupation. Any modifications to the HVAC system or the physical plan should be noted. An initial evaluation of the system's performance relative to its design goals should also be made. Table 4.2 outlines the principal components of a building which should be surveyed both at the time of initial inspection and in subsequent detailed follow-up. Table 4.3 details potential sources, both inside and outside, that may affect indoor air quality in

Table 4.4 Indoor Environmental Climate and Comfort Factors[a]

Factor	Parameters
Thermal	Dry-bulb temperature
	Wet-bulb temperature
	Vertical temperature gradient
	Plane-radiation temperature
	Omnidirectional air velocity (drafts)
Acoustic	Full bank sound level
	Frequency, intensity, type
Vibration	Frequency and amplitude
Lighting	Full-spectrum analysis
	Quantity (intensity)
	Quality (flickering, color, glare, or other problems)

[a]For further guidance, see ASHRAE (1985).

structures. Table 4.4 lists indoor environmental, climate, and comfort factors that can affect the occupants of a space.

After this first-stage assessment, an experienced investigator may detect the source of the problem. If remedial steps cannot be identified, then a more detailed investigation must be undertaken. However, at this point, the problem should have received sufficient description to permit development of a hypothesis and specification of the protocols necessary for further exploration.

SURVEY MONITORING: THE SECOND STAGE OF INVESTIGATION

The second stage of investigation often has three components: system evaluation, definition of microenvironments, and environmental screening. A system evaluation usually begins with a review of specifications, interviews with relevant personnel, and direct inspection of the premises. The evaluation also covers comfort controls in terms of sensor location, set points, and access. It is also important to establish the lines of responsibility for comfort conditions and the actions of facility operators in response to occupant requests. A more thorough system evaluation consists of analyzing (measuring) airflow through diffusers and other mechanical devices, both for supply and exhaust. Heating and cooling coils, drip pans, and filters should be inspected and maintenance schedules reviewed. The evaluation should also address the thermal loads of the building as originally designed and subsequent changes that could affect building load.

The concept of microenvironments is essential to building investigations (see Chapter 5). For the protocol circumstances of a building investigation, microenvironments may be defined as spaces sharing a common HVAC system, a ducted air supply, a zone, or a floor of a building. Microenvironments could also be defined as locations in which employees experiencing similar complaints are located. The concept of microenvironments should drive the sampling plan since

each sampling location is generally assumed to be representative of a homogeneous environment. Therefore, variation of measurements within a microenvironment must be less than the variance between different microenvironments. The outdoors also represents one or more microenvironments and may be sampled to establish background levels. However, a close inspection, and possibly sampling, of external sources that may impact a building may be required. There may be substantial variation in the air of various external areas of the building, which should be accounted for in the sampling scheme.

Five types of areas should be considered in developing a sampling strategy: (a) areas with the most susceptible occupants; (b) areas with potential sources; (c) areas with the least effective ventilation; (d) control areas having the least problems; and (e) outdoor air.

Environmental screening describes potential contaminant levels or other physical conditions in the space. Data can be collected with real-time survey monitors, such as those for carbon monoxide, carbon dioxide, temperature, humidity, and light levels, or integrated measurements can be used for respirable particulate matter or volatile organic compounds. For some contaminants (e.g., asbestos or microorganisms), bulk samples or surface samples are the most cost-effective means of identifying potential sources. The equipment used for making measurements should be calibrated in the anticipated range of field measurements both before and after sampling. The calibration procedures should be traceable to primary standards. (See Tables 4.6 through 4.11 for selected instrumentation suitable for building surveys.)

Depending on the results of the initial screening survey, additional information may be required to characterize fully the problem building. Table 4.5 summarizes additional considerations in planning a more detailed environmental survey.

Selection of Parameters to Be Measured Information gathered during the initial stages of investigation can define a set of contaminants and/or environmental conditions (i.e., temperature, relative humidity, drafts, air exchange rate, and other factors) which need to be monitored. These parameters can usually be obtained from a history of the building, an inventory of products used in the building, locations of potential sources, and a history of occupant complaints.

Table 4.5 Survey Design

Selection of physical/chemical contaminants to be measured
Time scale of measurements, duration, frequency
Establishment of required level of detection
Selection of instrumentation
Selection of sampling locations
Quality assurance program
Data analysis and presentation

Time Scale of Measurements The time scale of environmental measurements should be related to the potential health effects of interest. This can be refined further to reflect individual time and activity patterns that may have an important impact on overall exposures. Guidance in deciding on an appropriate sample duration to assess the impact of specific contaminants can come from relevant medical and toxicologic literature. For example, if there are short-term exposure limits for specific pollutants, the pollutants may have a significant short-term toxic effect and therefore should be evaluated with this concern in mind. Long-term integrated samplers can be used to characterize exposures to pollutants that cause toxic effects after chronic exposure.

Since integrated sampling methods average the concentrations of pollutants over the duration of the sample, they do not provide information on short-term excursions and peak concentrations which may be an important consideration in assessing individual exposures to pollutants. Furthermore, integrated samples generally do not capture information on cyclic exposures or variations that can occur throughout the sampling period. The critical concern in developing any sampling strategy is that samples are collected during the entire anticipated exposure period. The intermittent nature of many exposures requires that short-term sampling does not replace carefully formulated protocols for assessing individual exposures. Frequently the duration of sampling is limited by the collection media employed. For such methods it may be necessary to collect successive samples to ensure that any exposure events are effectively captured. For some pollutants, continuous sampling and analytical instruments with strip chart recorders or data loggers may be needed, as used for outdoor monitoring.

Time scales of interest can be seasonal, weekly, daily, or of shorter duration. The episodes of exposure may fall into a regular pattern, or they may be sporadic and unpredictable. External sources may impact pollutant levels, and meteorologic factors may have important influences on overall exposures. A historical review of complaints can help in determining the appropriate time scale for measurement.

The evaluation should consider that complaints by building residents or occupants may precede the monitoring and environmental assessment of the building by several weeks or more. The environmental conditions that produced the symptoms among occupants may have been transient or altered after complaints were made, and thus relating current measurements to past symptoms may be misleading.

The adverse effects experienced by occupants may be displaced from the relevant exposures or conditions in place and in time. For example, an individual may become sensitized to a contaminant over a period of time and then respond to much lower levels than had been encountered initially; cancer may follow the onset of an exposure by many years; asthmatics may experience bronchoconstriction hours after exposure to an agent rather than immediately; exposure that affects the fetus during the first trimester of pregnancy may be manifest only after birth. The investigator must understand the temporal relationship between exposures to various agents and the temporal evolution of injury, symptoms, and disease and the limitations of extrapolating measurements over time and place, particularly if changes of occupancy, function, material, ventilation, or external conditions have taken place.

Required Level of Detection Ideally the level of detection for instrumentation and analytical methods should be determined by the level of a particular contaminant expected to impact health or well-being. However, for many indoor pollutants, the needed scientific evidence is unavailable, particularly across the entire spectrum of sensitivity. At times trade-offs must be made among availability of instrumentation, portability, degree of obtrusiveness, and cost of analysis. To conduct a valid sampling program, the lower limit of detection must be assessed before going into the field; ideally it should be 10 percent of the desired change, whether in relation to levels associated with a health response or to an environmental standard. As general guidance, setting a lower detection limit of 1 percent of the occupational threshold limit value (TLV) or permissible exposure limit should be encouraged.

Selection of Instrumentation Tables 4.6 through 4.11 list selected methods and techniques for measuring air pollutants which are suitable for indoor air quality investigations. These can be divided into the categories of direct measurement techniques, passive sampling with active analysis procedures, and active sampling with active analysis procedures. Often the choice of instrumentation depends upon the required level of detection and the time scales of interest.

Selection of Sampling Locations Indoor monitoring always occurs in a dynamic environment, and the design of measurement surveys and the interpretation of results should appropriately consider the complex and changing nature of the monitored environment. Building occupants are not typically confined to a single location, and fixed location monitoring might not adequately represent personal exposures. For example, exposure to asbestos may be very low for most occupants in a building that has asbestos-containing materials, but maintenance and services employees, while running computer and telephone cables above the acoustical ceiling tile, could experience substantially higher fiber exposure as the material is disrupted. Similarly, higher radon levels are often found in basements, whereas in upstairs living areas the concentration can often be one-half to one-quarter of the basement concentration. Observation of occupant activity patterns, understanding of the ventilation system and air movement, and knowing the location of potential pollutant sources should guide investigators in selecting the sampling locations. It may be necessary to monitor in "control" areas or in other buildings for comparison. Depending upon the contaminants and conditions being examined, outdoor (upwind and downwind) monitoring might be required.

Quality Assurance and Control Adequate quality assurance and quality control procedures should be employed to ensure the accuracy of the data collected (Corn

1985; NIOSH 1984). The foremost consideration must be whether or not an adequate number of samples has been collected. Sampling statistics can be used for this purpose, and a pilot study may be needed. An evaluation of the variation among results is an important consideration in assessing how many additional samples must be collected to characterize the environment fully. Consideration should be given to the possible variation of contaminant concentrations over both time and space.

The quality assurance and control program should include field blanks, replicates, split samples, and spiked samples as appropriate. A certain number of replicate samples should be collected to assess the precision of sampling and analysis methods. Furthermore, an appropriate number of field blanks should be collected, generally two for each of ten actual samples. The field blanks should be retained independently of media blanks, which can be used by the laboratory to assess extraction efficiency or media contamination. Samples sent to a laboratory should be randomly numbered and presented in a blind manner to avoid potential conflicts and to ensure against bias by the analysts. It may be advisable to "split" samples and send them to the same and another independent laboratory for analysis; this approach uncovers systematic bias in the results of a particular laboratory. Any laboratory used for an investigation should have an internal, documented quality assurance and control program. For some types of samples, such as organic vapors collected on adsorbents or metals collected on filters, the recovery efficiencies of the analyses should be reported. If there is potential litigation, the laboratories should maintain records of instrumentation and calibration and of raw output for each analysis.

HEALTH AND COMFORT ASSESSMENT: THE THIRD STAGE OF INVESTIGATION

Environmental monitoring may fail to provide clear evidence of an agent or condition that can be causally associated with the reported symptoms or complaints. Measurements are performed after complaints have been made, and the originally inciting conditions may have been changed in response to concerns about particular pollutants. The monitoring methods may not have been sufficiently sensitive at the levels actually associated with the reported problem or may have failed to detect an unusual temporal pattern.

Therefore, it might be necessary to formulate a third, more comprehensive, stage of investigation, which includes a more thorough inquiry on symptoms and complaints. To correlate the subjective responses of building occupants with the objective measurements obtained during the investigation, a detailed occupant evaluation should be conducted. The evaluation might include collection of medical and symptom information related to the workplace and to all other environments. Various clinical diagnostic tests may be indicated, such as serum precipitins against antigens associated with hypersensitivity pneumonitis, or spirometry, a test of pulmonary function.

In some cases, the investigation may require documentation of symptom rates and thus, addition of an epidemiologist to the investigating team. Self-administered questionnaires have been used in many building investigations. The technique can be useful for identifying clustering of symptoms by location or in groups of employees categorized by time of occurrence and other factors. Although the approach of administering questionnaires to measure symptom occurrence appears straightforward, the responses are prone to bias and cannot be validated readily. Data collection from nonexposed control subjects may facilitate interpretation of the response by exposed persons.

Evaluations are usually conducted among occupants who are aware of potential health and comfort concerns. Job action and/or litigation may be pending. In such emotionally charged situations, there is a strong potential for reporting bias. Even without such obviously stressful conditions, reporting bias may occur. For example, women may have higher complaint rates than men, and complaint rates from public sector employees may tend to be higher than from private sector employees (Finnegan and Pickering 1987). Work status, dissatisfaction with the work station, and work pressures may be reflected in complaints obtained with self-completed questionnaires. Consultation with a psychologist may be warranted.

Investigations are often begun well after the onset of complaints. Environmental monitoring and/or contemporary comfort conditions can suggest a situation quite different from that initiating the original occupant complaints. However, retrospective reconstruction of exposures and symptoms by questionnaire is difficult, and therefore failure to find clear associations among symptoms, contaminant levels, and environmental conditions is not unexpected. Facility managers may have already adjusted HVAC systems or made other modifications in response to occupant complaints. In new or modified buildings, high emission rates of contaminants from building materials or furnishings may have led to the onset of complaints whereas months later, measurements may fail to detect high concentrations as emission rates drop.

Buildings are complex and often house multiple functions. A school building, for example, may have laboratories, classrooms, offices, and vocational education shops. Investigators should not search for a single causative condition but should consider causative agents in each type of environment. For example, some occupants might work in an area in which water damage has caused mold to grow; others may sense the uncomfortable vibrations caused by heavy equipment; and others may have inadequate ventilation. Nonspecificity of symptoms may make identification and resolution of all independent problems an impossible task.

Even in light of these limitations, further environmental monitoring in the occupied space is warranted at this phase of the investigation. However, measurements made to characterize conditions in the space in earlier phases of an investigation should now be performed in conjunction with a dynamic HVAC system evaluation in order to assess the occupied space as changes are made in the operating parameters of the building. In addition to monitoring potential contaminants in the space, objective measurements of other environmental parameters such as thermal, acoustic, vibration, and lighting conditions may also be indicated (Table 4.4).

This portion of the study requires a detailed understanding of the measurement systems available, the use of surrogate measurements such as tracer gases when appropriate, and the relationship of measurements to overall building operations and occupant activities. The conditions present during a building investigation may not be the same as those during the periods of maximum complaints. From the data gathered in earlier phases of the study, an understanding of how the system operates will have been obtained. Using this information, the investigator may artificially manipulate the HVAC system controls to create a "worst case" situation while correlating real-time measurements with system operations. This same approach can be used in a proactive approach to optimize system performance.

MEASUREMENT OF INDOOR AIR POLLUTION

The remaining sections of this chapter provide a guide to the tables (Tables 4.6 to 4.11) summarizing indoor air monitoring equipment. Although the tables are not comprehensive, they do contain brief descriptions of examples of the more common types of equipment currently used for building investigations and indoor air quality research (Lioy and Lioy 1983; ACGIH 1989). Earlier in this chapter, the factors to be considered in the selection of instruments and/or analytical methods were reviewed. Equally important choices must be made on the required frequency of sampling, location, sample duration, level of detection, ancillary measurements such as ventilation rates, and quality assurance protocols.

Often, a choice must be made between continuous measurements from direct reading instruments and integrated measurements. Both types have advantages and disadvantages, and the selection should reflect the purpose of the investigation. Some human responses are likely to be associated with short-term excursions, even as short as seconds or minutes. For example, odor, taste, and allergic responses can follow a single breath containing some contaminants. Obviously, direct reading or very short-term integration would be more appropriate for characterizing pollutants that so quickly produce responses. On the other hand, for contaminants that are associated with chronic effects on health, the long-term integration of measurements is more relevant. For contaminants such as chlorinated volatile organic compounds and radon, it is more appropriate to measure over weeks to months to smooth out the short-term fluctuations and to provide a more biologically appropriate measure of exposure. Nevertheless, even short-term continuous measurements of radon and pesticides can be very helpful in studying sources and factors influencing concentration such as subslab and/or basement depressurization.

DIRECT MEASUREMENT TECHNIQUES

These instruments can provide continuous or short-term integrated (over minutes) on-site measurements. They are direct reading and do not require that samples be taken to a laboratory. The pollutants for which direct measurement techniques are available include respirable suspended particulate matter (RSP), fibers,

carbon monoxide, carbon dioxide, nitrogen dioxide, volatile organic compounds, SO_2, and radon.

Respirable Suspended Particulate Matter A variety of devices are currently available for the direct measurement of particulate matter in the respirable size range (Table 4.6). Many of the devices collect particles on filters and typically provide results as milligrams or micrograms per cubic meter of air sampled. Other equipment uses optical techniques to assess the number of particles. The optical approaches for the direct measurement of RSP in air are often based on the near-forward light-scattering properties of fine particulate matter.

The mass of RSP can be measured directly with several innovative techniques. In the early 1970s, the bureau of mines directed the development of direct reading gravimetric dust monitors, which are no longer made. These devices measure the reduction in β-rays (high-energy electrons) from a safe radioactive source; the β-energy detected is reduced by the mass of dust deposited on a filter or impactor plate separating the source from the detector. Because the dust mass must build up to a measurable level, these devices measure a time-averaged value, but the measurement times can be as short as several minutes in very dusty areas or longer in less dusty areas. Since β-absorption by matter is relatively independent of the elemental nature of the dust for light elements, the measurement provides a good representation of total levels of dust mass.

Other techniques for RSP measurement involve the combination of impaction or electrostatic precipitation and piezoelectric resonance. An airstream first passes through an impactor or cyclone to remove the nonrespirable particles. The respirable particles are deposited by an electrostatic precipitator onto the quartz crystal sensor. The difference in oscillating frequency between the sensing and reference crystals is monitored and displayed during the measurement. At the end of the measurement period the actual concentration in mg/m^3 is displayed. Impactors with cutoff diameters are available for these devices in the range of 0.5–10.0 μm. In evaluating results obtained by this device it should be noted that semivolatile compounds that have been adsorbed onto the surface of the collected particulate material will be included in the total measured mass. This approach contrasts with the filter sampling technique in which continued sampling may drive off these semivolatile compounds from particle surfaces.

An additional technology currently available for the real-time direct measurement of RSP mass incorporates a tapered tubular element that is set into oscillation by a feedback amplifier. A vacuum pump attached to the tube's base draws the gas through a filter mounted on top of the tube. Particles become trapped in the filter. A microcomputer calculates the mass of the particles based on the change in frequency of vibration. This device can provide continuous mass measurement at flow rates ranging from 1 to 5 liters/min and can compute total mass, mass rate, or mass concentrations.

Table 4.6 Selected Examples of Available Equipment for Indoor Particulate Pollution[a]

Sampler	Source	Comments
Integrated gravimetric collection on filters	Several manufacturers, cyclones, preseparators, filters, and pumps	Detection limit depends on flow rates, duration, balance and preconditioning of filters before weighing[b]
Impactors and filters	Personal exposure monitor MSP Corporation 7949 Country Road 11 Maple Plains, MN 55359	4 liters/min flow rates. Cut size variable but available at 2.5 and 10 μm
Integrated gravimetric; particles <10-μm or <2.5-μm diameter	MS & T Impactor Air Diagnostics Inc. RR 1, Box 445 Naple, ME 04055 (207)583–4834	4 and 10 liters/m; mass flow controller for 14-day timer, double impactor for sharp cut; fixed location
Instantaneous (2/10 s); TSP or RSP; 0.1-10-μm forward light scattering	Miniram (personal aerosol monitor) Ram-1 larger device MIE, Inc. 213 Burlington Road Bedford, MA 01730 (617)275–5444	Miniram, range 0.01–10 mg/m^3 or 0.1–100 mg/m^3. Averaging times, 10 s to 8 h TWA[c]. Ram-1 range, 0.001–200 mg/m^3 calibrated with Freon-12 or by reference to gravimetric method
Semi-instantaneous; RSP fraction using piezoelectric balance	Piezobalance (model 3500) TSI, Inc. P.O. Box 64394 St. Paul, MN 55164 (612)483–0900	Less reliable for concentration <10 μg/m^3 at 2-min averaging. Averaging time is variable. Difficult to calibrate (needs chamber tests or comparison to other methods)
Continuous; RSP submicron light-scattering multisensor monitor	Handheld aerosol monitor (HAM) PPM, Inc. 11428 Kingston Pike Knoxville, TN 37922 (615)966–8796 HUND 401 Broadway New York, NY 10013 (212)219–2468	Lower detection limit about 10 μg/m^3. Can set zero and check span point in field but is calibrated by comparison with other methods
Light scattering for fiber detection	Fibrous aerosol monitor (FAM-1) MIE, Inc. 213 Burlington Road Bedford, MA 01730 (617)275–5444	Counts all fiber types per cm^3 by detecting scattered light from fibers rotating in oscillating electric field. Detection, 0.1 f/cm^3 for 1 min, 0.001 f/cm^3 for 100 min, 0.0001 f/cm^3 for 1,000 min

[a]Particles can be measured using a variety of techniques. Using cyclone or impactor separators, smaller size fractions can be collected on filters. Mass can also be measured using the optical properties of particles. For the most part, measuring particles requires equipment costing several hundred to a few thousand dollars. Equipment using filters require that they be preweighted and postweighted in a temperature- and humidity-controlled room. Particle sizes are commonly referred to as TSP (total suspended particulate matter). RSP (respirable suspended particulate matter), PM_{10} (particles <10-μm aerodynamic diameter), submicron sizes (<1 μm aerodynamic diameter). RSP size refers to a specific ACGIH cut curve where 90 percent of >10-μm, 50 percent of 3.5-μm, and 10 percent of 2-μm size particles are excluded.

[b]Filters can be Teflon, Nuclearpore, glass-fiber, or quartz, among other types. They can be analyzed for mass, particulate phase organics, pH, nitrates, sulfates, fibers, metals, and other contaminants with proper attention to handling.

[c]Time-weighted average.

Fibers Real-time monitoring of airborne fibers, including asbestos, can be achieved by a technique similar to that used for optically measuring respirable particulates (Table 4.6). A two-step sensing procedure is used to count fibers independent of the presence of nonfibrous particles; the fibers are induced to rotate rapidly by the application of a rotating electric field, and the resulting light-scattering signature from the oscillation of the fibers is detected during illumination by a helium-neon laser-generated light beam.

Carbon Monoxide Carbon monoxide (CO), a fairly nonreactive chemical, oxidizes to form the more stable carbon dioxide. Several detectors make measurements using the principle of electrochemical oxidation (Table 4.7). Although other air pollutants can interfere with the detection of CO by this approach, these pollutants can be removed by an inlet scrubber such as a Purafil filter. Ambient air is actively drawn past a catalytically active electrode or, in other devices, is allowed to diffuse passively across an electrochemical cell that oxidizes CO and produces a signal proportional to the CO concentration in the sample airstream.

Carbon Dioxide The measurement of carbon dioxide (CO_2) concentration is based upon this compound's characteristic absorptive band in the infrared range (at a wavelength of 4.25 μm) (Table 4.7). Monitors used for CO_2 can be either dedicated units set up specifically and only for CO_2 or other general purpose instruments that can be adjusted for CO_2 but are also used for other chemicals such as CO, formaldehyde, or total hydrocarbons. The amount of infrared energy absorbed is proportional to the concentration of the compound being analyzed.

Nitrogen Dioxide The instrumentation available for the real-time measurement of nitrogen dioxide (NO_2) is similar in principle of operation to that for measuring CO (Table 4.7). Filters are required, however, to provide specificity and to remove interference from other oxidizable chemicals such as methane and CO. Gas scrubbers are needed to remove potential interference from such agents as chlorine, ethyl mercaptans, methyl mercaptans, sulfur dioxide, ozone, and hydrogen sulfide when these chemicals are at concentrations equivalent to the NO_2.

Volatile Organic Compounds This topic is covered in more detail in Chapter 11. The measurement of many volatile organic compounds can be achieved by the same infrared absorbance technique described for CO_2 (Table 4.8). Infrared analyzers detect individual compounds by varying the analytical wavelength and path length of the device.

Other devices are less specific (Table 4.8). Many organic chemicals have ionization potentials of less than 10.6 electron volts (eV) whereas the normal air gases such as nitrogen and oxygen have ionization potentials of 12 eV or greater. *Ionization* refers to the formation of ions due to the absorbance of energy. In one device employing ionization, a miniature lamp emits very short wavelength ultraviolet (UV) radiation that has sufficient energy to cause "photoionization" when it strikes

Table 4.7 Selected Examples of Sampling Equipment for Indoor CO, CO_2, and NO_2 Pollutants

Sampler	Source	Comments
CO: continuous electrochemical	ECOlyzer 2000, 6000 Energetic Sciences, Inc. Division of Becton Dickinson and Co. 6 Skyline Drive Hawthorne, NY 10532 (914)592–3010	Various ranges 0–50 ppm, 0–100 ppm, etc.; portable and personal versions available; alarm option, cells expendable, LOD[a] ~2 ppm
CO: continuous electrochemical	Interscan Corporation P.O. Box 2496 21700 Nordhoff Street Chatsworth, CA 91311 (213)882–2331	Various ranges; cells expendable, LOD[a] ~1 ppm
CO: passive diffusion	Lab Safety Supply Co. P.O. Box 1368 Janesville, WI 53547 (608)754–2345	LOD[a] 50 ppm for 8 h; will produce color change
CO: passive diffusion detector	Quantum Eye Quantum Group, Inc. 11211 Sorrento Valley Road Suite D San Diego, CA 92121 (619)457–3048	Simple color change detector, not for permanent use, not quantitative
CO: detector tube, grab sample	National Draeger, Inc. P.O. Box 120 Pittsburgh, PA 15230 (412)787–8383	Range 5–700 ppm by color change; semiquantitative
CO: detector tube, grab sample	Toxic gas detector system Matheson-Kitagawa P.O. Box 85 932 Paterson Plank Road East Rutherford, NJ 07073 (201)933–2400	Range 5–50 ppm by color change on stain tube; semiquantitative
CO_2: continuous infrared	Portable infrared CO_2 monitor 4776 GasTech, Inc. 8445 Central Avenue Newark, CA 94560 (415)794–6200	Range 300 to >5000 ppm; ambient levels typically 350–450 ppm
NO_2: continuous electrochemical	Interscan Corporation P.O. Box 2496 21700 Nordhoff Street Chatsworth, CA 91311 (213)882–2331	Various ranges; cells expendable; >20 ppm
NO_2: continuous electrochemical	Transducer Research, Inc. 1228 Olympus Drive Naperville, IL 60540 (708)369–1336	Introduced 1989; >2 ppb, built-in data logger, zero
NO_2: personal and alarm	MDA Scientific 405 Barclay Boulevard Lincolnshire, IL 60069 (800)323–2000	2–3 ppm; 1/3 TLV electrochemical cell based 15 min to 8 h; TWA
NO_2: passive diffusion tubes	Environmental Sciences and Physiology Harvard School of Public Health 665 Huntington Avenue Boston, MA 02115 (617)432–1165	LOD[a] 500 ppb for a 1-h exposure (5 ppb for 100 h)
NO_2: passive tubes and badges	Micro Filtration Systems 6800 Sierra Court Dublin, CA 94568 (415)828–6010	Contact manufacturer
NO_2: diffusion badge	Environmental Sciences and Physiology Harvard School of Public Health 665 Huntington Avenue Boston, MA 02115 (617)432–1165	LOD 50 ppb for a 1-h exposure (5 ppb for 10 h)

[a]Limit of detection.

the molecules of certain chemicals. The instrument continuously draws air into a tiny ionization chamber that is flooded with UV light. As ions are formed, they migrate to the electrodes and cause a measurable change in the electric current, which is indicated in the LCD display. These devices cannot distinguish between different pollutants; the signal produced represents a composite of all different ionizable pollutants. However, the instrument response may be calibrated for a particular compound.

Radon The direct measurement of radon relies on the interaction of emitted α-particles with a coating of ZnS(Ag) on a glass tube, which causes a flash of light (scintillation) detectable by a photomultiplier tube (Table 4.9). The response of this tube to the light is an electrical signal. This type of device, called a *continuous radon monitor*, samples the ambient air by pumping air into a scintillation cell after passing it through a particulate filter that removes dust and radon decay products. As the radon in the air decays, the ionized radon decay products plate out on the interior surface of the scintillation cell. The continuous radon monitor may have continuous flow through the cell or fill it periodically. In either case, the instrument must be calibrated at known radon concentrations to obtain the conversion factor used electronically to convert count rate to radon concentration.

INTEGRATING DEVICES: PASSIVE SAMPLING

The pollutants for which passive sampling techniques are available include NO_2, formaldehyde, and radon. Exposure must be determined by an estimate of concentration and duration with respect to the detection limit for each device.

Table 4.8 Selected Examples of Available Equipment for Indoor Organic Air Pollutants

Sampler	Source	Comments
Organic vapors	Industrial Scientific Corporation 355 Steubenville Pike Oakdale, PA 15071 (412)758–4353	
Organic vapors	OVM Logger (model 580A) Thermo Environmental Instruments, Inc. 8 West Forge Parkway Franklin, MA 02038 (508)520–0430	General organic vapor monitor detects by photoionization. Detects down to 0.1 ppm benzene in air
Organic vapors	Portable gas chromatographs Thermo Environmental Instruments, Inc. 8 West Forge Parkway Franklin, MA 02038 (508)520–0430	Four detectors possible: electron capture flame ionization thermal conductivity photoionization
Organic vapors: portable gas chromatograph	Century OVA (portable organic vapor analyzer) Foxboro Company Foxboro, MA 02035 (203)853–1616	Total organic vapor detector (~0.2 ppm); selected organic vapor detector
Organic vapors: portable gas chromatograph	Photovac IOS (portable air analyzer) Photovac International, Inc. 741 Park Avenue Huntington, NY 11743 (516)351–5809	Total organic vapor detector; selected organic vapor detector including benzene, C4-C8 hydrocarbons, mercaptans, halocarbons
Organic vapors: hydrocarbon chemical reaction tubes	National Draeger, Inc. P.O. Box 120 Pittsburgh, PA 15230 (412)787–8383	Stain-tube detectors; semiquantitative
Organic vapors: charcoal badges	3M Corporation Technical Service Department 3M Center St. Paul, MN 55144 (612)733–1110	Depends on vapors and sampling times; minimum level, 10/mg, requires lab analysis
Organic vapors: thermal ionization	TIP Air Analyzers Photovac International, Inc. 741 Park Avenue Huntington, NY 11743 (800)387–5700	Semiquantitative response to several compounds. Can be calibrated to respond relative to that compound
Organic vapors and other gases: infrared detector	MIRAN portable air analyzers Foxboro Company South Norwalk, CT 06856 (203)853–1616	Tunable infrared wavelength, needs separate calibration for each gas
Formaldehyde: passive samplers	GMD Systems, Inc. Old Route 519 Hendersonville, PA 15339 (412)746–1359	LOD[a] 0.2 ppm for 15 min; 0.005 ppm for 8 h

(continued)

Table 4.8 *(continued)*

Sampler	Source	Comments
Formaldehyde: diffusion tube	Air Quality Research, Inc. 901 Grayson Street Berkeley, CA 94710 (415)644–2097	LOD[a] 0.01 ppm for 7-day exposure; 1.68 ppm for 1 h
Formaldehyde: Pro-tek adsorption badge	E.I. Dupont Company Applied Technical Division North Walnut Road P.O. Box 110 Kennett Square, PA 19348 (800)344–4900	1.6 to 54 ppm/h up to 7 days or 0.2 to 6.75 ppm for 8-h exposure
Formaldehyde: diffusion monitor	3M Corporation Technical Service Department Building 260-3-2 3M Center St. Paul, MN 55144 (612)733–1110	LOD[a] low as 0.8 ppm for 1 h, equal to 0.1 ppm for 8 h, and 0.005 ppm for 1 week
Formaldehyde: automated wet chemistry/colorimetry	CEA TGM 555 CEA Instruments, Inc. 16 Chestnut Street P.O. Box 303 Emerson, NJ 07630 (201)967–5660	Wet chemistry colorimetric sampler. Detection limit 0.002 up to 5 or 10 ppm, depending on range setting

[a]Limit of detection.

Nitrogen Dioxide Several passive monitoring devices for the measurement of oxides of nitrogen have been developed (Palmes 1981; Woebkenberg 1981) (Table 4.7). The Palmes tube, which consists of an acrylic tube with one fixed cap and one removable cap, contains stainless steel screens impregnated with triethanolamine that absorbs NO_2. Spectrophotometric analysis is carried out in the laboratory to determine the concentration of NO_2. These tubes have a detection limit of about 500 ppb-h. A one-week exposure should detect levels less than 5 ppb. An NO_2 filter badge, which uses the same absorbing material but with a larger surface area, has a detection limit of about 50 ppb-h.

Formaldehyde Passive diffusion monitors for the measurement of formaldehyde (HCHO) work on a principle similar to that for NO_2. For this air contaminant, however, a glass-fiber filter treated with sodium bisulfite at the fixed end of the tube reacts with and removes the HCHO. Collected HCHO is quantified in the laboratory using the chromotropic acid procedure.

Radon Three passive sampling techniques are available for the measurement of radon (Table 4.9). Charcoal canisters can be used for short-term average measurements (two to five days), and α-track detectors (ATD) can be used for longer term measurements of up to weeks or months. A third type of passive radon detector is the Electret Passive Environmental Radon Monitor "E-PERM," available from Rad-Elec. Inc.

Table 4.9 Radon Gas ^{222}Rn Detectors

Device	Description	Manufacturer	Manufacturer Specifications: Sensitivity	Manufacturer Specifications: Averaging Time	Sampling Features: Passive (P) or Active (A)	Sampling Features: Integrating (I) or Continuous (C)
Charcoal canister detector	Radon adsorption/γ-scintillation (NaI crystal)	F & J Specialty Products Inc.[a] P.O. Box 660065 Miami Springs, FL 33266 (305)888–0383 (charcoal canister maker)	0.2 pCi/liter[b]	2–7 days	P	I
Charcoal vial detector	Radon adsorption/α-scintillation (liquid)	Niton Corporation 74 Loomis Street Bedford, MA 01730 (617)275–9275	0.1 pCi/liter[b]	2–7 days	P	I
ATE (e.g., Track Etch® Radtrak®)	CR-39/plastic/ microscopy	TERRADEX Corporation[a] (a Tech/OPS Company) 3 Science Road Glenwood, IL 60425 (800)528–8327	0.4 pCi/liter	≥3 months to 1 year	P	I
E-PERM®	Electret ion detector	Rad Elec, Inc. 5330J Spectrum Drive Frederick, MD 21701 (301)694–0011	1 pCi/liter	2–7 days; 2–52 weeks	P	I
AT EASE® detector	Solid-state detector	Sun Nuclear Corporation 415-C Pineda Court Melbourne, FL 32940 (305)259–6862	$60 \frac{\text{cpm}}{\text{pCi/liter}}$	4, 8, 12, or 24 h	P	C
Survivor 2®	Ion chamber	Threshold Technical Products, Inc. 11325 Reed Hartman Highway Cincinnati, OH 45241 (800)458–4931	0.1 pCi/liter (minimum reading)	12 h	P	C
femto-TECH® radon monitor (model R210F)	Pulsed ion chamber	*femto*-TECH, Inc. P.O. Box 8257 1325 Industry Drive Carlisle, OH 45005 (513)746–4427	$0.3 \frac{\text{cpm}}{\text{pCi/liter}}$	~3 min	P	C
Radon Tracker® (model RGM-2)			N/A	N/A	A	C
Eberline® radon gas monitor (model RGM-2)	α-Scintillation	Eberline Instrument Corp. P.O. Box 2108 Santa Fe, NM 87504 (505)471–3232	$4 \frac{\text{cpm}}{\text{pCi/liter}}$	1 h	A	C
EDA® PERM (model RDT-310)	Thermoluminescent detector (TLD)	EDA Instruments, Inc. 4 Thorncliffe Park Drive Toronto, Ontario M4H 1H1 Canada (416)425–7800	N/A	N/A	P	I
PYLON® portable radiation monitor (model AB-5) *and either*		Pylon Electric Development Company, Ltd. 147 Colonnade Road Ottawa, Ontario K2E 7L9 Canada (613)226–7920				
PYLON® Lucas cell (models 300 and LCA-2)	α-Scintillation		0.3 pCi/liter	1–99 s, min, or h	A	C
or PYLON® passive gas monitor (model PRD-1)	α-Scintillation		$1.1 \frac{\text{cpm}}{\text{pCi/liter}}$	1–99 s, min, or h	P	C

Source: "Radon/Radon Progeny Measurement Proficiency Program Cumulative Report" (updated periodically), Office of Radiation Programs, U.S. EPA, Washington, D.C., 1988. Lists laboratories that are certified to do these tests.

[a]Many companies provide measurement service; see source footnote.

[b]Estimated.

Charcoal canisters are passive integrating detectors that can be used to determine the average radon concentration over a short sampling interval. At the laboratory, the canisters are analyzed for radon decay products by placing the canister directly on a γ-detector to count γ-rays of energies between 0.25 and 0.61 MeV. The charcoal canister system can be calibrated by analyzing canisters exposed to known concentrations of radon in a calibration facility.

An ATD consists of a small piece of plastic enclosed in a container with a filter-covered opening. α-Particles emitted by the radon decay products in air strike the plastic and produce submicroscopic damage tracks. At the end of the measurement period, the detectors are returned to a laboratory, and the plastic is placed in a caustic solution that accentuates the damage tracks, which are then counted using a microscope or an automated counting system. The number of tracks per unit area estimates the radon concentration in the air; a conversion factor derived from data generated at a calibration facility is used for the calculation.

In the E-PERM detector, an electret (a material with a permanently embedded electric field) is placed in an air chamber. A filter on the chamber allows air and radon to enter but blocks already existing ions. When the chamber is opened, radon enters and creates ions (charged particles) during decay. When the ions strike the electret, its charge is reduced, and the charge on the electret is subsequently analyzed to calculate the radon level.

Tables 4.9 and 4.10 list the many radon and radon progeny detectors that are currently available. The Environmental Protection Agency (EPA) has tested several devices in its radon measurement proficiency program. Information on commercial radon testing can be obtained from EPA Office of Radiation Programs in Washington, D.C., or from regional EPA or state offices.

INTEGRATING DEVICES: ACTIVE SAMPLING

The pollutants for which active sampling techniques are available include RSP, asbestos, formaldehyde, volatile organic compounds, and microbiologicals. Active sampling involves the use of a sampling train with a collection medium (solution, filter, or other absorbing bed) and a pump. The pump draws the air sample into the detector.

Respirable Suspended Particulate Matter RSP can be measured in air by filtration to collect the sample with subsequent analysis for mass or composition (Table 4.6). Particles can be size fractionated by utilizing specially designed inlets. The filters used to collect the RSP must be preweighed and then reconditioned and reweighed in a controlled humidity environment to control for the uptake of water vapor during sampling. Sampling must be performed at a calibrated volumetric rate in order for the results to be presented in terms of mass per unit volume of air sampled.

Asbestos The Asbestos Hazard Emergency Response Act (AHERA) of 1986 (U.S. EPA 1987) provides for the establishment of federal regulations for the inspection, sampling, and assessment of asbestos-containing materials. In monitoring for asbestos hazards, four types of microscopic analysis techniques are commonly used. Various state and federal accreditation programs have been established to ensure competence. Polarized light microscopy allows identification of asbestos by viewing the morphology of fibers directly, using stereoscopic polarized light examination. Phase-contrast microscopy is widely used for assessing worker exposure to airborne fibers, using the NIOSH 7400 method and the OSHA reference method. Transmission electron microscopy (TEM) embodies state-of-the-art technology for analyzing airborne concentrations of asbestos fibers. Fibers as small as 0.1 μm in length are discernible. Asbestos fiber types can also be identified positively through the use of TEM or scanning electron microscopy (SEM) analysis.

The traditional technique for the assessment of asbestos in the workplace has been optical microscopy. This approach typically uses a microscope setup to utilize phase contrast and requires a trained operator. Analysis can be performed on suspect materials, wipe samples, or air samples collected on an appropriate filter substrate.

Formaldehyde The measurement of formaldehyde in air can be achieved by using impingers for collection in an absorbing reagent followed by spectrophotometric analysis in a laboratory. Absorbing reagents are either deionized distilled water that is kept chilled during sampling or a 1 percent solution of sodium bisulfite. Analysis can be performed by the chromotropic acid method or the pararosaniline method.

Volatile Organic Compounds The diverse properties of organic compounds, including less volatile insecticides and pesticides, pose a difficult challenge for making measurements (see also Chapter 11). A suitable collection medium, such as Tenax, Sphericarb, and activated carbon, traps or adsorbs these molecules without permitting reactions, backdiffusion, or breaking through (Table 9.8). Whole air samples can be collected in evacuated stainless steel cylinders or in nonreactive bags. Organic compounds are recovered from these collection devices and analyzed usually by gas chromatography and mass spectrometry or gas chromatography with other types of detectors.

Microbiologicals The measurement of microbiologically active organisms in the air can be achieved by using impinger samplers that draw known volumes of air past plates of growth media (Table 4.11). The plates can then be incubated at appropriate temperatures to foster the growth of the specific organisms of interest, whether bacteria or fungi. Counting the number of colonies formed yields results in terms of colony-forming units per volume of air sampled. The sample can be cultured to determine the particular organisms present.

Table 4.10 Radon Progeny Detector

Device	Description	Manufacturer	Manufacturer Specifications		Sampling Features	
			Sensitivity	Averaging Time	Passive (P) or Active (A)	Integrating (I) or Continuous (C)
RAD® radon/thoron daughter monitor (model M-1)	Filter and CR-39 plastic (RPISU[a])/ microscopy	R.A.D. Service & Instruments, Ltd. 50 Silver Star Boulevard Scarborough, Ontario M1V 3L3 Canada (416)298–9200	0.1 mWL[b]	3 days to 2 weeks	A	I
"Radon Sniffer" working level meter	Filter/solid state detector	Thomson & Nielsen Electronics, Ltd. 4019 Carling Avenue Kanata, Ontario K2K 2A3 Canada (613)592–3019	1 mWL[b] (minimum reading)		A	C
EBERLINE® radon working level systems (models WLM-1 and WLR-1)	Filter/solid state detector	Eberline Instrument Corporation P.O. Box 2108 Santa Fe, NM 87504 (505)471–3232	0.02 mWL[b] is lowest detectable level	1 h	A	C
EDA® working level monitor (model WLM-30)	Filter/solid-state detector	EDA Instruments, Inc. 4 Thorncliffe Park Drive Toronto, Ontario	1 mWL[b]	Programmable	A	C
EDA® RPISU[a] (model 225)	Filter/TLD	M4H 1H1 Canada (416)425–7800	N/A	≥3 days[c]	A	I
alphaNUCLEAR® alphaSMART® (model 760)	Filter/solid-state detector	alphaNUCLEAR company 1125 Derry Road East Mississauga, Ontario L5T 1P3 Canada (416)676–1364	0.05 mWL[b]	Programmable	A	C
PYLON® portable radiation monitor (model AB-5) *plus* α-Detection assembly (model AEP)	Filter/α-scintillation	PYLON Electronic Development Company, Ltd. 147 Colonnade Road Ottawa, Ontario K2E 7L9 Canada (613)226–7920	0.2 mWL[b]	1,699 s, min, or h	A	C

[a]Radon Progeny Integrating Sampling Unit.
[b]Milli working level.
[c]Rough estimate.

Table 4.11 Selected Examples of Sampling Equipment for Indoor Microbiologic Pollutants

Sampler	Source	Comments
Slit impactor rotating agar	Casella Bacteria Sampler Casella London, Ltd. Regent House Britannia Walk London N1 7ND England	Rotating disc containing agar; heated 37°C for 24 h; different agar for different organisms; need laboratory for culturing and identification
Impaction into agar dish	Andersen 1-cubic ft/min viable (microbial) sampler Andersen Samplers, Inc. 4215-C Wendell Drive Atlanta, GA 30336	Typically operating with last stage only of a multiple-stage impactor; air accelerated through jets to impact on agar (nutrient) dish; organisms must grow into colonies for identification. Note: adjustment of colony-forming units/m^3 required
Slit impactor on rotating drum	7-day volumetric spore trap Burkard Manufacturing Company Woodcock Hill Industrial Estates Rockmansworth Hertfordshire WDS 1PL England	Samples for fungus spores and pollens by impaction onto adhesive-coated strip; rotating drum provides 24-h to 7-day sampling; viable and nonviable organisms must be microscopically identified.

SUMMARY

Problem buildings generally require rapid investigation to uncover the causes of the problems and effectively remedy them. Any obvious defects of the building or mechanical system should be identified in the first phase of the investigation. Measurements made during the subsequent stage of investigation should indicate whether an eminent hazard exists in the building. Underlying problems may often be identified and resolved at this point in the investigation. However, because a building is complex and several factors may simultaneously impact a space, an investigation must often enter into a more extensive phase. Through the manipulation of many parameters controlling building systems, review of the building's history regarding occupant activities, furnishings and other aspects of use, and correlation of this information with the complaint history of the occupants, the investigator should gain an understanding of the building, its actual and expected performance, and its potential impacts on the occupants. At this point the effective resolution of the problem should be possible.

As a component of all building investigations, the investigators must communicate their findings to both building management and the occupants. A report should be sufficiently detailed to include design, methods, results, and limitations of interpretation. Definitive causal associations are often impossible to make in building investigations; however, remedial steps can many times be inferred. The recommendations should include corrective and preventive measures.

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