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Indoor Air Quality in Office Buildings: A Technical Guide

Canada

Indoor Air Quality in Office Buildings: A Technical Guide

A Report of the
Federal-Provincial Advisory Committee
on Environmental and Occupational Health

Également disponible en français sous le titre :
“Guide technique pour l’évaluation de la qualité de l’air dans les immeubles à bureaux"

93-EHD-166
(Revised 1995)

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Health Canada

Published by authority of the
Minister of National Health and Welfare

Cat. H46-2/93-16 Erev
ISBN 0-662-23846-X

The views expressed in this report are those of the author, and the publication does not constitute an approval or agreement on the part of Health Canada. Copies of the Report are available from:

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Funding for this project was provided by
Department of National Health and Welfare

Definitions

Building-related illness
A specific illness with a known cause that is a result of exposure to an indoor agent. Examples are Legionnaire's disease and Pontiac fever.

Health
A state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity.

Indoor air quality
The physical, chemical, and biological characteristics of indoor air in non-residential workplaces with no internal industrial processes or operations that can affect the comfort or health of the occupant.

Sick building syndrome
A set of symptoms related to chemical, particulate or biological exposure that cannot be related to a specific cause but are alleviated when the occupant leaves the building. Individuals report symptoms such as headaches, nausea, fatigue and drowsiness, to eye, nose, and throat irritation.

Stressors
Environmental parameters, such as lighting, noise, vibration, ergonomics, overcrowding and other psychosocial issues which may affect a person's perception and satisfaction of the built environment and indoor air quality.

Thermal comfort
A state of mind in which a person feels satisfaction with the thermal environment. The factors affecting thermal comfort are air temperature, mean radiant temperature, stratification, air motion, relative humidity, activity level and clothing.

Ventilation rate
The amount of outside air that is supplied to the interior space.

Acronyms

ACGIH	American Conference of Governmental Industrial Hygienists
AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
FID	Flame ionization detector
GC	Gas chromatography
HVAC	Heating, ventilating, and air conditioning
IAQ	Indoor air quality
MS	Mass spectrometry
PCBs	Polychlorinated biphenyls
PID	Photoionization detector
RSP	Respirable suspended particulates
SBS	Sick building syndrome
TLV	Threshold limit value
TVOC	Total volatile organic compounds
VOC	Volatile organic compound

Units

μm	Micrometre (micron, M)
CFU	Colony-forming units
g	Gram
L	Litre
m	Metre
m^3	Cubic metre
min	Minute
ppb	Parts per billion
ppm	Parts per million
s	Second

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1. Introduction and Scope

1.1 Purpose of Document

This document will provide guidance for those people responsible for conducting indoor air quality (IAQ) investigations in office buildings. It will assist them in determining the cause of poor IAQ, in establishing at what point specific professional services are required, and in defining the methodology and scope of a particular IAQ study.

1.2 Users

This report is designed for use by property managers, building maintenance staff, health and safety officials, and consultants working in the occupational environment field. It will facilitate communication between those responsible for investigating IAQ complaints and all other concerned persons.

1.3 Investigation Methods

An IAQ investigation attempts to isolate and mitigate one or more problems of the office building environment. The approach is solution-oriented and systematically narrows the range of possibilities. The investigator must search through the clues carefully to solve the problem. Most complaints, especially in smaller buildings, can be handled on site by a person who understands the building operation and the technical framework of IAQ issues.

The investigation generally proceeds from simple consultation and observation through a cycle of information gathering, hypothesis formation, and testing until a solution is obtained.

2. Background

2.1 Sick Building Syndrome and Related Complaints

IAQ has become a significant environmental issue. The number of related complaints has increased in recent years with increased building tightness, the growing use of synthetic materials, and energy conservation measures that reduce the amount of outside air supply. Modern office equipment (e.g., photocopiers, laser printers, computers), cleaning products, and outdoor air pollution can also increase the level of indoor air contamination. The reactions to these contaminants have led to the phenomenon of sick building syndrome (SBS).

The causes of occupant complaints are multi-factorial and often elusive. It can involve chemical, microbiological, physical and psychological mechanisms. However from a rational perspective, contaminant source control is the most effective general means to improve IAQ.

Analysis of air samples may fail to reveal significant concentrations of any one contaminant, so the problem is often attributed to the combined effects of many pollutants at low concentrations, complicated by other environmental factors. For example, several factors influence thermal comfort, such as overheating, underheating, humidity extremes, drafts, and lack of air circulation. Likewise, odours are often associated with a perception of poor air quality, whether or not they cause symptoms. Environmental stressors such as noise, vibration, overcrowding, and poor workplace design and lighting can produce symptoms that may be confused with the effects of poor air quality. Further, physical discomfort or psychosocial problems (such as job stress) can reduce tolerance for substandard air.

2.2 Factors Affecting Indoor Air Quality

The indoor environment results from the interaction of the site, the climate, the building system, the potential contaminant sources (e.g., furnishings, moisture sources, work processes and activities, and outdoor pollutants), and the building occupants. Some of these factors and sources are listed in Table 1.

The heating, ventilating, and air conditioning (HVAC) system is designed to provide thermal comfort (temperature and humidity control), distribute outdoor air to occupants, remove odours and contaminants through the use of exhaust fans or dilute them to acceptable levels, and control pressure relationships between rooms. Bathrooms, kitchens, and smoking lounges should be maintained at negative pressure so that pollutants generated there do not migrate elsewhere. Computer rooms should be maintained at positive pressure to keep out dust.

2.3 Ventilation Guidelines

The generally accepted guidelines for ventilation and IAQ are ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality*, and ASHRAE Standard 55-1992, *Thermal Environmental Conditions for Human Occupancy*.

Table 1.
Factors and Sources Affecting Indoor Air Quality and Comfort

Factor	Source
Temperature and humidity extremes	Improper placement of thermostats, poor humidity control, inability of the building to compensate for climate extremes, tenant-added office equipment and processes
Carbon dioxide	People, combustion of fossil fuels (e.g., gas and oil furnaces and heaters)
Carbon monoxide	Automobile exhaust (garages, loading docks, air intakes), combustion, tobacco smoke
Formaldehyde	Unsealed plywood or particleboard, urea formaldehyde foam insulation, fabrics, glues, carpets, furnishings, carbonless copy paper
Particulates	Smoke, air inlets, paper, duct insulation, water residue, carpets, HVAC filters, housekeeping
Volatile organic compounds (VOCs)	Copying and printing machines, computers, carpets, furnishings, cleaning materials, smoke, paints, adhesives, caulking, perfumes, hairsprays, solvents
Inadequate ventilation (insufficient outside air, insufficient airflow, inadequate circulation)	Energy-saving and maintenance measures, improper system design or operation, occupant tampering with HVAC system, poor office layout, system unbalanced
Microbial matter	Stagnant water in HVAC system, wet and damp materials, humidifiers, condensate drain pans, water towers

3. Communication Strategy

Procedures should be defined for handling complaints and for communicating information before, during, and after an investigation. Lines of communication should identify key people, such as occupants, building staff, workplace health and safety committees, management and union representatives, and health and regulatory agencies. Ultimately, however, the building owner will have to resolve the problem. Cooperation and early action can lead to a successful solution. Without open communication, any IAQ problem can become complicated by frustration and distrust, delaying its resolution.

Because standards of comfort vary from one individual to another, it is probably impossible to satisfy all occupants of a building. In any building population, there may be some environment-hypersensitive individuals who are adversely affected by a wide range of environmental factors at relatively low exposure levels. For these special cases, a good deal of personal detective work may be required to determine the cause of the sensitivity, to achieve control over symptoms, and to establish working and living conditions, lifestyle changes, and medical treatments that may lead to a reduction in sensitivity over time.

It is in the building manager's best interest to respond promptly and seriously to all complaints about the indoor environment and to establish credibility through open communication with the building occupants. Building managers should not underestimate the anxiety and frustration that can result if occupants believe that no action is being taken or that important information is being withheld.

Effective communication during IAQ investigations should include the following steps:

- Define the complaint area, based upon the location and distribution of complaints (the extent of the complaint area may be revised as time goes on).
- Identify key people and form a balanced inspection team. Building occupants can be valuable allies in solving IAQ problems, particularly in observing odours or patterns with respect to IAQ complaints. To encourage this cooperation, it is advisable to take occupants' theories into account during the investigation.

- Establish a system of recording the timing and location of complaints. This could include complaint logs and/or occupant questionnaires. Written records are important to the understanding of IAQ problems.

- Notify building occupants of the scope and purpose of any upcoming investigations. This information can be posted, distributed, or addressed at a health and safety committee meeting.

- Make the final results and proposed implementation plan available. Provide progress reports. Feedback and cooperation are important.

4. Initial Assessment

The initial assessment is a fact-finding exercise to document the complaint. During the initial assessment, problems are defined and their severity is assessed. Background information is collected that will be helpful in identifying possible pollutants and locating their sources, including information on the building itself, on the kinds of symptoms employees have been experiencing, and on the period of time over which symptoms have been experienced.

A copy of the floor plans is helpful, as observations can be recorded on them directly. The investigator should also review any documents available on the history of the building, including modifications – particularly recent ones. A person familiar with the building's HVAC system should be available to assist the investigation, and any persons required for access should be identified.

4.1 Initial Walkthrough

A walkthrough is needed to gain a first-hand, visual appreciation for the building's design, floor plan, and ventilation system. This walkthrough should provide enough information to enable the investigator to form a hypothesis, perhaps recommend simple modifications, and formulate a plan for the subsequent investigation.

Minimal measurements are taken during an initial walkthrough. The investigator can use specific checklists or worksheets and may focus on a localized problem area.

Occupants should be interviewed, especially complainants. Information on symptoms, timing of onset and relief, and spatial patterns of complaints should be gathered in order to define the problem as completely as possible. The investigator should also note any obvious sources of internal or external pollutants.

4.2 Reviewing the Complaint Area

The following general indicators help to call attention to pollutant sources:

- odours (see Table 2)
- overcrowding
- unsanitary conditions
- dust
- moisture problems, visible fungal growth
- staining and discolouration of ceiling tiles, walls or carpets
- presence of chemical substances.

Table 2.
Odours as Problem Indicators in Office Buildings

Description	Problem	Complaints
Auto exhaust, diesel fumes	Carbon monoxide	Headaches, nausea, dizziness, tiredness
Body odour	Overcrowding, low ventilation rate (high carbon dioxide levels)	Headaches, tiredness, stuffiness
Musty smell	Microbial material, wet surfaces	Allergy symptoms
Chemical smell	Formaldehyde, pesticides, other chemicals	Eye, nose, and throat irritation
Solvent smell	VOCs	Odour, allergy symptoms, dizziness, headache
Wet cement, dusty, chalky smell	Particulates, humidification system	Dry eyes, respiratory problems, nose and throat irritation, skin irritation, coughing, sneezing
Sewage gas odour	Water traps dry in floor drains in washrooms or basement	Foul smell

Other activities involved in reviewing the complaint area include the following:

- Compare the original uses of the complaint area and surrounding rooms with the present use. Has occupant density increased? Have work areas been rearranged or converted to other uses? Has new equipment, such as computers, printers, photocopiers, or humidifiers, been added?
- Identify areas where remodelling, repair, or redecorating activities are in progress or have recently been completed. Check that proper control procedures are being used to isolate dust, paint fumes, and other off-gassing contaminants related to the activity.
- Check temperature and humidity to see that the complaint area is in the comfort range. Check for visible mould due to condensation, elevated humidity levels or water leaks.
- Check carbon dioxide as an indicator of ventilation adequacy in occupied areas. Carbon dioxide levels above 1000 parts per million (ppm) in office environments indicate that the ventilation rate is low and that other airborne contaminants are accumulating.
- Observe airflow patterns. Look for areas of poor mixing, short-circuiting (supplies and returns close together), and obstruction of supply and exhaust ducts.

4.3 Defining the Problem and Drawing Conclusions

At the conclusion of the initial assessment, it should be possible to identify:

- the nature of the complaints
- the number of occupants affected
- building system parameters that can be related – by timing, location, etc. – to the complaints
- possible HVAC deficiencies and general operating and maintenance conditions
- signs of occupant interference with the ventilation system
- obvious internal and external pollutant sources.

If the specific source of the problem has been identified and a solution proposed, the investigation will stop until the changes are implemented and the effect is evaluated. If a solution cannot be found or other problems have come to light, it is necessary to proceed with a more detailed investigation.

5. Detailed Assessment

During a detailed assessment of an indoor environment, air quality indicators and pollutant sources are investigated and measured and the HVAC system is checked. Tools include checklists and calibrated measuring equipment.

Some measurements may require the use of complex instruments and laboratory analysis. Specialists may be required at certain stages of the diagnostic process, and a team approach is advisable. An industrial hygienist, chemist, or engineer may be able to measure and evaluate a variety of suspected pollutants, whereas a mechanical engineer can evaluate the effectiveness of the design and operation of the ventilation system. Because most office buildings rely on the HVAC system to provide contaminant control by ventilation, it is important to understand the performance of the system.

5.1 Collecting Information about Air Quality Indicators

Before discussing the individual pollutant sources, we will examine the factors that should be considered when making a measurement, the equipment and methods employed, and the investigative procedures.

5.1.1 Purpose of Measurements

Air sampling should not be undertaken until some or all of the other investigative methods available have been exhausted. The sampling strategy should be based on a comprehensive understanding of how the building operates and the nature of the complaints.

Air sampling of the various indoor contaminants is needed to address the problem of SBS. High readings may be considered conclusive evidence of a problem. However, low readings do not necessarily preclude the existence of subtle or intermittent air quality problems.

It may be desirable to take certain preliminary air quality measurements that are indicative of common IAQ concerns, such as temperature, relative humidity, air movement, and carbon dioxide.

Air sampling makes it possible to:

- establish baseline conditions so that levels measured in problem areas can be compared with concentrations at other times and at other locations
- compare indoor with outdoor air quality
- test a hypothesis about the source of the problem
- confirm that a control approach has the desired effect of reducing pollutant concentrations or improving ventilation
- reveal the existence of compounds associated with particular types of building problems (e.g., a carbon dioxide reading over 1000 ppm is an indicator of underventilation; a carbon monoxide reading over 5 ppm is an indicator of unvented combustion products or vehicle exhaust entrainment)
- compare measured concentrations with occupational exposure standards and with public health and comfort guidelines for specific pollutants.

5.1.2 Sampling Considerations

There are several ways to locate sampling sites for an IAQ investigation. A building may be divided:

- by individual HVAC zones
- by types of HVAC zones (interior vs. perimeter)
- by complaint vs. non-complaint areas
- by relationship to major sources (e.g., proximity to smoking areas, printing shop)
- by complaint types.

It is best to measure pollutants arising from the building structure, furnishings, or ventilation (e.g., formaldehyde, VOCs, microbial contamination) in the morning if the ventilation system is turned off overnight or over the weekend. Pollutants generated by the occupants (e.g., carbon dioxide) or by the occupants' activities (e.g., use of photocopiers) are best checked toward the end of the working day in order to detect the highest concentration.

The time of year is also an important consideration. If the building is on an economizer cycle, outdoor air supply will be less during very cold or very hot weather, which generally makes pollutant concentrations higher. Also, some sources are seasonal, emanating from humidifiers and air conditioning systems.

Proper operation of IAQ measuring equipment and proper calibration are critical to the success of any sampling program. Calibration to ensure accurate measurements is usually done using a known standard on the low (zero) and high (span) range of the expected measurement.

Sampling strategy should be designed to assess worst-case conditions, such as instances of maximum equipment emissions, minimum ventilation, or disturbance of contaminated surfaces. Worst-case sampling results can be very helpful in characterizing maximum occupant exposure.

Sampling time can vary in length according to the lower detection limit of the analytical method, the emission characteristics of the source, the degree to which pollutant concentrations vary, and any specific objectives of the measurement.

Experience has shown that the vast majority of chemical pollutants will be present at concentrations far below those known to cause health-related problems. Although the capability of these substances to cause discomfort in trace concentrations, alone or as part of a mixture, is not well understood, it is clear that the use of traditional industrial hygiene standards and criteria does not provide a meaningful basis for the evaluation and subsequent resolution of IAQ complaints.

5.1.3 Overview of Monitoring Methods and Equipment

Simple measurement methods are available for the non-specialist, such as the building operator or property manager who has received complaints about air quality in a building. These measurements are easy and quick to perform.

Failure to detect IAQ problems through measurement of individual parameters does not mean that no problem exists. Chances are that an irrelevant parameter was measured, the measurement was taken at an inappropriate time, or existing permissible exposure standards are simply not adequate to determine if one air contaminant or a combination of contaminants constitutes a comfort risk for some people.

Measurement effectiveness can vary according to whether the method is passive or active, whether the instrument is a sampler, analyser, or direct-reading device, and whether measurements are continuous or grab (spot). Passive samplers such as badges are inexpensive and simple to deploy; however, they usually require laboratory analysis to determine the contaminant level. An active sampler, such as the colorimetric sampling tube, is also inexpensive and will provide on-site spot measurements for carbon monoxide, carbon dioxide, and other specific pollutants. However, it has limited sensitivity.

Direct-reading instruments can be employed for spot checks or can be set up for continuous monitoring of specific pollutants. However, they are expensive and require calibration and some operator training.

5.2 Individual Source Evaluation

This section focuses on IAQ indicators and pollutants, discussing each in terms of characteristics, guidelines, ideal levels, and health effects. Also provided is a checklist for use in a walkthrough specific to each indicator or pollutant source and a presentation of the measurement methods. This is followed by a discussion of remediation strategy as applicable.

5.2.1 Temperature and Humidity

Temperature and relative humidity are two of several parameters that affect thermal comfort. Satisfaction with the thermal environment can also be influenced by such factors as radiant temperature, air velocity, occupant activity level, and clothing.

ASHRAE Standard 55-1992, *Thermal Environmental Conditions for Human Occupancy*, presents guidelines that are intended to achieve thermal conditions that at least 80% of the occupants would find acceptable or comfortable.

Relative humidity levels below 25% are associated with increased discomfort and drying of the mucous membranes and skin, which can lead to chapping and irritation. Low relative humidity also increases static electricity, which causes discomfort and can hinder the operation of computers and paper-processing equipment. High humidity levels can result in condensation within the building structure and on interior or exterior surfaces and the subsequent development of moulds and fungi. In most Canadian cities, ideal indoor relative humidity levels are 35% in the winter and 50% in the summer. ASHRAE specifies a range between 25 and 60%.

In large buildings, the air supply is humidified over the winter season, usually by a water spray or steam system. Water spray humidifiers require regular scheduled maintenance to control water quality. Steam humidifiers are cleaner and easier to maintain, but use more electrical power. In the summer, the air conditioning dehumidifies the outdoor air supply.

5.2.1.1 Checklist. During the preliminary walkthrough, comfort-related problems will have been identified from occupant complaints and from observation.

a. Temperature

- Check for any evidence of high or low temperatures. Are these due to occupant interference, such as installation of heaters or new equipment?
- Check for local sources of heating or cooling, such as uninsulated floors over a garage or overhang, solar load through windows, or cold window frames.
- Ensure that thermostats are functioning, calibrated, correctly located, and not obstructed or enclosed.
- Check for evidence of thermal gradients; the floor-to-ceiling differential should not exceed 3°C.
- Check for a balanced air distribution network (even air circulation and air current). Do occupants use fans?
- Check for any obstruction of air circulation, such as high office partitions, taped diffusers, or perimeter units blocked by paper, books, or cabinets.
- Look for diffusers directly over occupants or close to return slots.

b. Relative humidity

- Check humidifier operation, including excess scale or rust, blocked nozzles, broken pump, and areas of stagnant, dirty water.
- Look for a defective or poorly calibrated humidistat located in the return air duct.
- Look for condensation caused by excess humidity or by insufficient thermal insulation of the building shell.
- Check for chemical additives used for water treatment.

5.2.1.2 Measurement Methods and Equipment. There are several methods of measuring temperature and relative humidity, ranging from a simple thermometer for temperature and a wet and dry bulb thermometer (psychrometer) for humidity to sophisticated electronic instruments equipped with solid state sensors.

Avoid sampling locations that are near machinery or heated directly by the sun or other sources of radiation. If possible, the operator should stand facing the air current so that the instrument receives the air first.

a. Psychrometers

A psychrometer measures relative humidity using the temperature difference between two temperature sensors, one of which is moist and cooled by an airstream. An electric fan (in the case of the powered psychrometer) or simple manual whirling of the device (in the case of the sling psychrometer) is employed to produce the airstream.

Sling psychrometers are inexpensive and simple to use; however, the results are unreliable. The instrument should be calibrated frequently against a primary standard, and the wick must be kept moist and clean. Powered psychrometers are more expensive but provide a direct and more accurate readout of relative humidity.

b. Hygrometers

Hygrometers are small, compact electronic units with a digital display for spot measurements or continuous logging of relative humidity. Some units also measure temperature and air motion.

A hygrometer employs a sensor that changes its resistance or capacitance as the humidity varies. The sensor is usually a hygroscopic salt or a small, thin film capacitor that absorbs moisture, producing a proportional output. Hygrometers should be calibrated at least once a year. Kits are usually available from the manufacturer, or the unit can be sent to a laboratory for calibration.

5.2.1.3 Strategy for Remediation. When thermal comfort complaints occur, the HVAC system's capacity to provide adequate heating or cooling and to humidify or dehumidify the occupied zone should be verified. Actual requirements may be quite different from original design parameters, especially if changes have occurred in the use of space, fit-up, layout, and occupancy or if new equipment has been introduced. Large heat-generating equipment may have to be ventilated separately or removed if the existing system cannot cool the space where it is located.

The operating and maintenance condition of the HVAC system and the control system should be in good working order and properly balanced and calibrated. Although zone control is important, so that, for example, a south-facing location can be cooled while a north-facing one is heated, individual occupant control would ideally provide thermal comfort to all, irrespective of location, clothing, and activity level.

Other remedial measures may include the following:

- Hot or cold surfaces may be insulated to reduce radiant heat gain or loss, reducing temperature gradients, drafts, and condensation. Windows may be insulated by adding another pane, reflective surface, or covering.
- Infiltration and exfiltration of the building envelope may be reduced by sealing openings and gaps and by maintaining a proper pressure differential between floors and between the inside and outside of the building.
- Ventilation and air circulation may have to be increased. An additional air handling unit (AHU), diffuser, or heater may have to be added to the problem area.
- System hours of operation may have to be extended to maintain environmental control during occupancy periods. For example, the operator may have to run the air conditioning system throughout the evenings during a hot spell to ensure an acceptable indoor environment at the start of the work shift.

5.2.2 Carbon Dioxide

Carbon dioxide is a colourless, odourless gas. It is a normal constituent of the atmosphere at 330-350 ppm. Its concentration in indoor air in office buildings can, under certain conditions, provide a good indication of the ventilation rate. It is generated indoors primarily through human metabolism. People in the office environment exhale carbon dioxide at a rate of about 0.3 L/min when performing light office duties.

Although the primary function of an HVAC system is to provide thermal comfort, some outside air must be introduced in order to dilute workplace-generated contaminants and odours. Because modern buildings have less natural ventilation (infiltration) than older ones, and because occupants, office equipment, and furnishings produce chemical contaminants, it is important to add relatively clean outdoor air to the occupied work space. The case against using outside air during the heating and cooling seasons is that additional costs are incurred to filter, heat/cool, humidify/dehumidify, and distribute the air. It is recognized today, however, that the requirements of energy conservation and IAQ must be balanced in order to provide occupants with a healthy, comfortable, and productive workplace. Salary costs for absent or unproductive employees can far exceed building operating costs.

The concentration of carbon dioxide indoors varies according to location, occupancy, and time of day, tending to increase during the day. Typical office levels are in the range of 600-800 ppm. ASHRAE Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality*, recommends a minimum ventilation rate of 10 L/s per person to ensure good IAQ in the office, using the ventilation rate procedure. The ASHRAE standard also provides an alternative performance method, the IAQ procedure, which uses guidelines for acceptable concentrations of certain contaminants as a means of achieving good IAQ. For normal occupancy and activities, this minimum outdoor ventilation rate of 10 L/s per person would result in a carbon dioxide concentration of 850 ppm at steady state conditions in the occupied space.

Carbon dioxide levels should be used with caution as an indicator of acceptable IAQ. The basic premise is that if the HVAC system is not removing carbon dioxide, then other indoor contaminants are probably accumulating proportionately. However, there may be a high indoor source of a contaminant irrespective of a low carbon dioxide level. Comparison of peak carbon dioxide readings between rooms and between air handler zones may help to identify and diagnose various ventilation deficiencies.

5.2.2.1 Checklist

- Study floor plans and details of renovations to assess potential problem areas, such as:
  - open office space that has been converted to closed offices (such closed offices may not contain thermostats, return or supply air diffusers)
  - places where structural alterations have resulted in space usage of a type different from that indicated in the plans (e.g., transformation of office space into a waiting room, conference room, or computer room).
- Note complaints about lack of ventilation, “lack of oxygen,” stuffiness, and symptoms such as headaches and fatigue, which may signal problem areas.
- Answer the following questions:
  - What are the high average or peak occupant densities? What was the design occupancy?
  - Are the outside air controls and dampers functioning properly?
  - Is the minimum outside air damper opening set at approximately 15%?

– Is there a source of contamination from the outside air?
– Are all air supply diffusers operational? Is the air stuffy or are odours present?
– Is there system intervention, such as blockage of the ventilation grilles?
– What time of day does the air seem to be worst? Is there an increased problem toward the end of the day?
– Are diffusers and exhaust outlets close together, thereby causing short-circuiting?
– Has any construction (e.g., walls, partitions) modified the ceiling return air pathway?

5.2.2.2 Measurement Methods and Equipment. Levels of carbon dioxide are normally highest in the late morning and late afternoon and vary with occupancy during the day. Also, outdoor air intake is usually at a minimum during the peak heating and cooling seasons.

Measurements should be taken at control locations, such as the outdoor air intake, the mixed air supply, the exhaust air plenum, places where the initial assessment has indicated high occupancy levels, and other locations where there are complaints of poor air quality. Carbon dioxide measurements taken at the air intake should be close to outdoor levels, otherwise exhaust is being entrained. The exhaust carbon dioxide level will indicate the average level for the building.

Spot samples can be taken, or continuous measurements can provide a detailed profile of concentration over time. To sample, the operator should stand away from the sampler/analyser to prevent contamination of the air sample with carbon dioxide from breath. Measurements are usually made between desk and head level.

It is good HVAC operating practice that indoor carbon dioxide levels at the start of the morning shift be close to outdoor levels. Extended system operating times and natural air infiltration should be used to achieve this goal. Although measurement of the volume of outdoor air may be beyond the capability of building personnel unless the air rate from the supply fan is known, the proportion of outside air can be estimated from temperature measurements of the outside air, return air, and mixed. The percentage of outdoor air is calculated as follows:

$$\text{Outside air (\%)} = \frac{T_{\text{mixed air}} - T_{\text{return air}}}{T_{\text{outside air}} - T_{\text{return air}}} \times 100$$

The accuracy of the calculation is proportional to the temperature differences. Alternatively, the percentage of outside air can be calculated in the same way using carbon dioxide measurements.

a. Direct-reading tubes

In the direct-reading colorimetric method, a hand pump is used to draw air through a glass tube packed with a specific compound. The length of stain observed in the sampling tube is proportional to the carbon dioxide concentration and is read directly from the sample tube. The tube can be used only once. The accuracy of the direct-reading method is ±25%.

Other direct-reading monitors sample by diffusion and are deployed for 1-8 hours. These devices provide an average carbon dioxide level for the measurement period and are an inexpensive way of obtaining a time-weighted average value.

b. Infrared analysers

Infrared analysers consist of sample and reference cells, a detector, and a broad band source of infrared radiation. These direct-reading continuous analysers respond quickly and can be moved from location to location to provide an immediate measurement of carbon dioxide. Care must be exercised to properly establish the zero and span settings and the device should be calibrated before and after each day of testing. The instrument must be allowed to reach thermal equilibrium before operation.

Advantages of the infrared analyser are portability, sensitivity, and instant and continuous monitoring capability. Disadvantages are its cost, its tendency to drift with time, its susceptibility to mechanical shock, and the need for frequent calibration.

5.2.2.3 Strategy for Remediation. Ventilation effectiveness can be improved by:

- adjusting and rebalancing the ventilation system (supply and return diffusers) to reflect current occupancy levels, and heat and contaminant generation locations
- increasing the outside air supply
- removing obstructions from the return plenum
- controlling pressure relationships, exhausting areas where pollutants are generated

- altering the source/distribution relationship by changing the physical arrangements of supply and return diffusers or furniture and partitions

- upgrading the air distribution system by increasing fan capacity in either the supply or the return system.

5.2.3 Air Motion

Air motion in a building is a readily identifiable comfort parameter representing the displacement of air by convection or ventilation. If air motion in an occupied space is inadequate, it may lead to complaints of stuffiness. The air pressure in the ducts may be too low for adequate airflow, or the ventilation system may be unbalanced.

Four air changes per hour provide gentle air movement as well as continuous dispersal of contaminants. Excessive air movement causes draft or unwanted local cooling of the human body. ASHRAE recommends that the average air movement in the occupied zone for the winter period not exceed 0.15 m/s; summer air movement should not exceed 0.25 m/s.

When building occupancy or use patterns change or when office equipment such as photocopiers, computers, and printers is added, it is likely that appropriate adjustments in air supply have been overlooked. To ensure that each diffuser provides good air movement throughout the area it serves, the system may have to be rebalanced.

Airflow is influenced by the combined action of controlled mechanical systems and natural, uncontrolled forces. Pressure differentials move airborne contaminants through windows, doors, cracks, holes, utility chases, stairwells, elevator shafts, and other openings.

5.2.3.1 Checklist

- Enquire about any recent change in the physical set-up and use of the space.

- Check supply air diffusers for excess airflow or blockage.

- If diffusers have deflectors, check that they are adjusted properly.

- Check return grilles for blockage.

- Check ceiling mixing boxes for proper control and damper positions.

- Take note of any exhaust and diffuser ducts that are in close proximity.

- Check condition of filters in perimeter units and ceiling systems.
- Check that ductwork is in good condition and properly connected.

5.2.3.2 Measurement Methods and Equipment. Air movement is usually measured both in ventilation ducts, where it is relatively rapid, and in the office, where a low speed must often be maintained.

a. Smoke tubes

One of the most useful devices for qualitative measurements of airflow and direction is the smoke tube, which can help track contaminant movement and identify pressure differentials. Smoke tubes are low-cost and are often employed during the walkthrough. Using a smoke tube in mid-room will help identify air circulation within the space. Dispersal within a few seconds suggests good circulation, whereas smoke that stays essentially still indicates poor circulation.

Smoke released near diffusers and grilles gives a general indication of air movement. The procedure assists in evaluating the supply and return system and in determining whether supply air actually reaches the work area. Since the “smoke” is usually an acid vapour take care not to inhale it.

b. Thermal anemometers

Thermal anemometers provide direct readout of air velocity. The airflow cools a sensor, usually a hot wire, in proportion to the velocity of the air. As the probe is non-directional, care must be taken to position the sensor properly.

c. Thermal comfort meters

Thermal comfort meters are capable of measuring all comfort-related parameters, such as mean radiant temperature, air temperature, humidity, and air motion. The parameters are integrated to produce a “level of comfort.” The units are expensive and the results inconclusive.

5.2.3.3 Strategy for Remediation

- Unblock diffusers and return grilles where necessary. Drafts caused by supply air diffusers can be deflected with baffles.
- Sometimes uneven thermal surfaces such as cold windows, ledges or floors can create uncomfortable convection currents. These can often be alleviated by simply insulating the cold surface.

- When occupied spaces are redesigned for changed space requirements, adequate airflow to the redesigned space needs to be verified. Flow system rebalancing may be necessary.

5.2.4 Carbon Monoxide

Carbon monoxide is a colourless, odourless, toxic gas that is a product of incomplete combustion. Carbon monoxide pollution occurs where combustion gases are not properly exhausted or are being re-entrained into the building. Carbon monoxide should be measured if there are complaints of exhaust odours or if there is some other reason to suspect a problem with internal combustion gases.

In office and commercial buildings, important sources of combustion contaminants include tobacco smoke, garages, and loading docks that are attached or have a pathway to working spaces. Air intakes located at ground level or adjacent to vehicles or other combustion sources can transport contaminants to areas served by the air handling system.

ASHRAE Standard 62-1989 indicates that the 8-hour average exposure limit for carbon monoxide should not exceed 9 ppm. However, levels above 5 ppm indicate the undesirable presence of combustion pollutants – once located, they should be exhausted.

Carbon monoxide is extremely toxic. It combines with haemoglobin in the blood, reducing the oxygen supply to the body. At elevated levels, symptoms of exposure include headaches, decreased alertness, flu-like symptoms, nausea, fatigue, rapid breathing, chest pain, confusion, and impaired judgement. The degree to which these symptoms occur depends on health status and individual variations in sensitivity, so specific responses at a given concentration will vary among individuals.

5.2.4.1 Checklist

- The study of floor plans and/or discussions with the building operator may reveal possible problem areas.
- Inspect the loading dock and parking garages:
  - Are they properly ventilated? Is the exhaust blocked off?
  - Are trucks or cars left running?
  - Is there an access route from the dock or garage to other building areas?
  - Are stairways, elevator shafts, and ducts acting as pathways for automobile exhaust and diesel fumes?

  - Are carbon monoxide sensors (for ventilation control) and alarms installed in the garage calibrated and operating properly?
  - Is ventilation switched on only at peak periods?
  - Is a diesel generator located near an air entry route?

- Inspect the office area:
  - Are the occupants ill or complaining of symptoms such as headaches, fatigue, dizziness, and nausea?
  - Are the occupants working near possible sources of combustion products?
  - Are stoves and other sources fitted with exhaust systems?
  - Do the odours or symptoms occur during the peak hours of incoming and outgoing traffic?
  - Are air intakes close to a street carrying heavy traffic or to other exhausts containing combustion products? Outdoor air intakes located below third-floor level can conduct fumes from vehicular traffic, parking garages, and loading docks.

5.2.4.2 Measurement Methods and Equipment. Measurements should be made near sources, complaint areas, stairways, and elevators linked to sources.

a. Direct-reading tubes

Direct-reading tubes are a low-cost form of measurement used for spot sampling. A known volume of air is drawn through a detection tube by means of a hand pump. The length of stain is proportional to the carbon monoxide level and can be read directly (in ppm) from the detector tube. However, the measurements are not exact, and the detection limit should be less than 5 ppm.

Long-term sampling tubes with a sampling pump can be used to obtain an average concentration over longer periods.

b. Electrochemical analysers

Electrochemical analysers are small, compact detectors that provide immediate, accurate results and are useful for survey work or continuous measurements. They sample air by diffusion or by use of a small pump. The monitor employs an electrochemical cell, where carbon monoxide is oxidized to carbon dioxide, and generates a proportional electrical signal.

These devices are less expensive than infrared analysers, are easy to use, and can operate for long periods of time on standard batteries. They require calibration for zero and span concentration.

c. Infrared monitors

Infrared monitors are light, direct-reading portable units. They are usually more expensive than electrochemical monitors. Some electrochemical and infrared monitors can store data, which can then be compared with traffic load.

The target gas is sensed by its characteristic absorption line in the infrared region of the electromagnetic spectrum. The detector generates an electrical signal output based on the difference in absorption between a reference and a sample cell.

5.2.4.3 Strategy for Remediation. Carbon monoxide levels higher than 5 ppm can indicate a problem. Problems can usually be mitigated by:

- ensuring that offices adjacent to parking garages and loading docks are under positive pressure
- increasing ventilation to the problem area
- closing pathways between the contaminated area and the occupied space, ensuring that doors are well sealed
- modifying the ventilation system (e.g., installing local exhaust or relocating outdoor air intake away from the exhaust area)
- modifying operating procedures (e.g., turning off engines while waiting for service)
- removing or relocating the source
- inspecting for leaks in gas-fired heating systems and for backdrafting of combustion products.

5.2.5 Formaldehyde

Formaldehyde is a colourless gas. A pungent odour often indicates its presence at a concentration greater than 0.2 ppm. Formaldehyde is present when vapours off-gas from building materials (e.g., carpets, particleboard, fabrics), cleaning fluids, and adhesives.

Indoor concentrations are dependent on the age of the source, ventilation rate, indoor and outdoor temperatures, and humidity. Formaldehyde concentrations can also vary by as much as 50% from day to day and from season to season.

The measured results can be compared with the various guidelines available; typical office levels should be under 0.1 ppm.

Formaldehyde is a known irritant and sensitizer. Symptoms include dry or sore throat, nosebleeds, headaches, fatigue, memory and concentration problems, nausea, dizziness, breathlessness, and burning, stinging, and pain in the eyes. Irritant effects have been associated with concentrations in the median range of 0.5 ppm, and concentrations as low as 0.01 ppm have been reported to affect sensitive individuals.

Animal studies indicate that formaldehyde is a carcinogen. The American Conference of Governmental Industrial Hygienists (ACGIH) has identified formaldehyde as a “suspected human carcinogen” and sets a ceiling threshold limit value (TLV-C) of 0.3 ppm.

5.2.5.1 Checklist

- Records should be examined for evidence of recent renovation: painting, installation of plywood or particleboard, replacement of carpets, and installation of new furniture.
- Enquire about cleaning procedures.

5.2.5.2 Measurement Methods and Equipment. Monitors for formaldehyde include grab, continuous, and time-averaged samplers. Some equipment can provide direct readouts of formaldehyde in parts per million, whereas others require laboratory analysis of the samples.

a. Direct-reading tubes

This method employs detector tubes containing a substance that reacts with formaldehyde to produce a measurable colour change. Tubes are available that span several sensitivity ranges. Concentrations are read directly from the calibrated tube by the length of the stain. The tubes require a hand-operated or mechanical pump.

This method is only marginally sensitive at normal indoor air levels but may be useful for source identification and evaluation. Some samplers can measure in the range of 0.2-5 ppm.

b. Chemical analysis

In chemical analysis, formaldehyde is first collected in a sorption medium, then treated chemically and analysed to determine its concentration.

Passive samplers are small portable dosimeters that sample by diffusion onto a treated medium. The sample is analysed by the investigator or in a laboratory using the colorimetric or chromatographic method. Passive samplers are inexpensive, require little training to deploy, and involve little equipment. The sensitivity is good in the ppb, and an average formaldehyde level is determined for the measurement period, usually one day to one week.

The active sampling methods require a pump and bubbler. Some training is recommended, and solutions or solid sorbents must be prepared and processed in a laboratory.

c. Electrochemical detector

The electrochemical detector is a direct-reading active analyser. Formaldehyde is electrochemically reacted at the sensing electrode, generating a current in proportion to the concentration. A small internal air pump samples the air continuously. The minimum detectable level is in the 0.02-0.05 ppm range.

Advantages of the unit are portability, quickness of response, simplicity of operation, and continuous measurement capability. Disadvantages are the cost, the need for some training for calibration and maintenance, and the limited lifetime of the sensor.

5.2.5.3 Strategy for Remediation. Formaldehyde should be minimized in indoor air through both source and ventilation control methods.

Source control methods include:

- removing or reducing the source (selecting products with reduced emission levels, relocating contaminant-producing materials to a better-ventilated space)
- sealing the source with a barrier, such as polyurethane varnish
- off-gassing furnishings and building materials in storage prior to installation.

Ventilation control methods include:

- increasing the flow of outside air during the occupied and non-occupied hours
- controlling air pressure relationships (local exhausting, eliminating pollutant pathways)
- controlling source/distribution relationships (relocating occupants, avoiding recirculation of contaminated air).

5.2.6 Particulates

Particulates are solid or liquid matter with aerodynamic diameters ranging from 0.005 to 100 μm. Dusts, fumes, smoke, and organisms such as viruses, pollen grains, bacteria, and fungal spores are solid particulate matter, whereas mists and fog are liquid particulate matter. Indoor particles come from both indoor and outdoor sources and can be drawn into the building via infiltration and outdoor air intakes. The mechanical ventilation system itself may be a source of particulates (e.g., humidifier additives, scale, rust, disinfectants, biological growth, duct and pipe insulation).

Fibres, synthetic or natural, are also classified as particulates. Asbestos fibres are not included in this report, as they are covered comprehensively in other publications. Product information sheets on respirable glass wool fibres bear the following caution: "Based on studies of laboratory animals, fibre glass wool has been classified as a possible cause of cancer." Although no comfort standards currently exist for respirable glass fibres, it would seem prudent to minimize exposure through safe work practices. Work areas being renovated should be sealed off, and damaged ceiling tiles, pipe insulation, sound barriers, etc., should be replaced or repaired.

The size range of concern to human health and IAQ is 0.1-10 μm. Particles smaller than 0.1 μm are generally exhaled, and most particles above 10 μm will be filtered by the nose. Particulates are classified as total suspended particulates (TSP) or respirable suspended particulates (RSP), which consists of those with particle size under 10 μm. Small particles that reach the thoracic or lower regions of the respiratory tract are responsible for most of the adverse health effects, and guidelines have been developed for those particles 10 μm or smaller (PM_{10}). ASHRAE Standard 62-1989 has adopted the U.S. Environmental Protection Agency PM_{10} standard of 50 $\mu g/m^3$ for annual exposure and 150 $\mu g/m^3$ for 24-hour exposure.

In office buildings, the average particulate concentration found in a non-smoking environment is 10 $\mu g/m^3$. In smoking areas, it can range from 30 to 100 $\mu g/m^3$.

Excessive levels of particulates can cause allergic reactions, such as dry eyes, contact lens problems, nose, throat, and skin irritation, coughing, sneezing, and respiratory difficulties. The effects of exposure to tobacco smoke particulates range from headaches and short-term irritation of the eyes, nose, and throat to aggravating the conditions of people with pre-existing diseases – including respiratory and heart disease, allergies to other substances, and cancer.

5.2.6.1 Checklist. Inspections should be carried out in areas that have been recently renovated, in areas where there have been complaints, and in the mechanical equipment room. The following questions should be asked when assessing the likelihood of particulate contamination:

- Are materials coming into the building through the air intake?
- Are the outside air dampers screened, and is the entry free of debris and dirt? Is there dust on surfaces?
- Is the filtering system designed for primary filters, rated between 10% and 30% dust-spot efficiency, and for secondary filters, rated between 40% and 85% dust-spot efficiency?
- Are filters installed and maintained properly?
- Are particulates entering the air from the humidification equipment (spray or ultrasonic humidifiers, chemical disinfectants, corrosion, rust)?
- Are there chalky marks or cement-like odours around the humidifier?
- Are there personal ultrasonic humidifiers in the workplace?
- Is there evidence of damaged insulation in the ducts or AHUs?
- Are there dirt marks or white dust on diffusers, indicating particulates entering from the ventilation system?
- Is smoking taking place anywhere in the building?

- Are large amounts of paper being stored or moved, or are there paper-shredding activities?

5.2.6.2 Measurement Methods and Equipment. Weight by volume of sampled air or particle count is measured. The exposure standard is by weight.

a. Gravimetric method

In the gravimetric method, a portable sampling pump is used to draw a measured volume of air through a filter enclosed in a cassette. Collected materials are deposited on the filter. The difference in the weight of the dried filter before and after sampling corresponds to the mass of particulates. Matched-weight filters are available to correct for humidity changes in the filter during and after sampling and to eliminate the need for weighing the filter before sampling.

The procedure uses a 37-mm filter and a calibrated pump capable of at least 8 hours of sampling at 2 L/min. The particulates can be further examined under a microscope to determine whether particles or fibres are present.

To separate particulates into size fractions, usually less than 10 µm, a nylon cyclone can be used. Another method uses a series of size-selective plates, or a cascade impactor, collecting particles at each stage on filters.

Filtration methods are the simplest and lowest-cost methods available; however, a precise balance and stringent quality control procedures are required. A large air volume must be sampled to obtain accurate measurements, which have a detection limit of 5 $\mu g/m^3$.

b. Optical scattering

In the optical scattering method, air passes through a size-selective inlet to an optical cell, where the presence of the particulates results in light scattering. The amount of scattering is related to the number of particles. Depending on the instrument and the length of the sampling period, levels of 0.001-200 mg/m^3 can be measured. Measurements are indirectly related to mass concentrations, as a factor is used to convert particulate number to weight. Some instruments provide particule counts and concentration by size range and are ideal for outdoor/indoor and site comparison.

These instruments provide immediate results and can be used by personnel without specialized training, which makes them a popular choice for surveys and walkthroughs.

c. Piezoelectric resonance

Piezoelectric monitors pass air through a size-selective inlet, and particles are electrostatically precipitated onto a quartz crystal sensor. The collected particles change the oscillation frequency of the crystal, and these changes are related to the collected particle mass. These instruments have a measurement range of 0.005-20 mg/m^3 and can be used by operators with little training.

Piezoelectric monitors can obtain true mass concentrations in real time. They do not provide samples for later analysis. They can be used with data loggers for continuous measurements.

5.2.6.3 Strategy for Remediation. Methods of reducing particulate levels are:

- controlling, exhausting, sealing, or relocating the source
- upgrading the filtering system
- increasing the outdoor airflow
- avoiding recirculation of air that contains contaminants.

High levels of particulates due to smoking are ideally controlled by banning smoking or, alternatively, by isolating the activity in a specially designed room maintained at negative pressure, with a dedicated exhaust.

5.2.7 Volatile Organic Compounds

The term "organic compounds" covers all chemicals containing carbon and hydrogen. Volatile organic compounds are those organic compounds that have boiling points roughly in the range of 50-250^{o}C. There are probably several thousand chemicals, synthetic and natural, that can be called VOCs. Of these, over 900 have been identified in indoor air, with over 250 recorded at concentrations higher than 1 ppb. Some of the most commonly encountered ones and their sources are listed in Table 3.

Table 3.
Commonly Encountered VOCs and Their Sources

Chemical	Source
Acetone	Paint, coatings, finishers, paint remover, thinner, caulking
Aliphatic hydrocarbons (octane, decane, undecane hexane, isodecane, mixtures, etc.)	Paint, adhesive, gasoline, combustion sources, liquid process photocopier, carpet, linoleum, caulking compound
Aromatic hydrocarbons (toluene, xylenes, ethylbenzene, benzene)	Combustion sources, paint, adhesive, gasoline, linoleum, wall coating
Chlorinated solvents (dichloromethane or methylene chloride, trichloroethane)	Upholstery and carpet cleaner or protector, paint, paint remover, lacquers, solvents, correction fluid, dry-cleaned clothes
n-Butyl acetate	Acoustic ceiling tile, linoleum, caulking compound
Dichlorobenzene	Carpet, moth crystals, air fresheners
4-Phenylcyclohexene (4-PC)	Carpet, paint
Terpenes (limonene, α-pinene)	Deodorizers, cleaning agents, polishes, fabrics, fabric softener, cigarettes

Outdoor levels of VOCs should be low (0.1 mg/m^3 or less) if there are no sources. Indoor levels may be substantially higher. Typical office levels range from a few micrograms to a few milligrams per cubic metre. All buildings contain a large variety of chemical sources, such as plastics, cigarette smoke, floor wax, cleaning compounds and substances associated with combustion, liquid-process printers, or copiers.

Identification and measurement of individual VOCs are expensive and time-consuming, and invariably the total is underestimated because the VOCs present at very low concentrations are difficult to identify or measure. The concept of total VOCs (TVOC) was developed to deal with this situation. Measurements of TVOC record total VOCs present without distinguishing different chemicals.

5.2.7.1 Standards. The threshold limit values (TLVs) for individual chemical substances that have been adopted by the ACGIH are not appropriate for office environments, for several reasons. For example, ACGIH TLVs apply to industrial workers who may be exposed to a few known contaminants at high concentrations over a 40-hour work week. Industrial workers are usually provided with adequate protective equipment (e.g., source ventilation, protective clothing or face masks, breathing equipment). In addition, the industrial workforce is generally made up of young, healthy, adult males.

Office workers, on the other hand, are exposed, without protective equipment, to a broad spectrum of contaminants at low concentrations over periods often longer than 40 hours per week. The synergistic effect of these compounds on occupant comfort is not known. As well, the population composition of the office workforce covers a much broader spectrum than that of the industrial workforce.

It would therefore seem that individual limits much lower than ACGIH TLVs are more appropriate. ASHRAE Standard 62-1989 recommends using one tenth of ACGIH limits for compounds for which comfort guidelines do not exist. Although there are at present no Canadian or U.S. standards for TVOC, target and action units of 1 and 5 mg/m^3 respectively, are being discussed. The European Community has prepared a target guideline value for TVOC of 0.3 mg/m^3, where no individual VOC should exceed 10% of the TVOC concentration.

5.2.7.2 Health and Comfort Effects. Research in Europe and North America has demonstrated that VOCs at concentrations much lower than the ACGIH TLVs can cause discomfort. Symptoms of low TVOC exposure include fatigue, headaches, drowsiness, dizziness, weakness, joint pains, peripheral numbness or tingling, euphoria, tightness in the chest, unsteadiness, blurred vision, and skin and eye irritation.

In an exposure range of 0.3-3 mg/m^3, odours, irritation, and discomfort may appear in response to the presence of TVOC together with thermal comfort factors and stressors. Above about 3 mg/m^3, one may expect complaints; above 25 mg/m^3, temporary discomfort and respiratory irritation have been demonstrated for a common mix of chemicals in an office building. Typical office levels cover a range from below to above the amounts found to cause discomfort.

Hypersensitive individuals can have severe reactions to a variety of VOCs at very low concentrations. They can react to organic compounds that are released by building materials, carpets, and various consumer products, including cosmetics, soaps, perfumes, tobacco, plastics, and dyes. These reactions can occur following exposure to a single sensitizing dose or sequence of doses, after which time a much lower dose can provoke symptoms. Chronic exposure to low doses can also cause reactions. Symptoms are usually non-specific and may be insufficient to permit identification of the offending compounds.

Because the available knowledge of toxicological and sensory effects of VOCs and their mixtures is incomplete, reduction of overall exposure to VOCs is desirable.

5.2.7.3 Checklist. Inspections should be carried out in complaint areas and in locations that are potential sources of VOCs, such as local printshops, photographic darkrooms, laboratories, and chemical storage areas.

The following questions should be asked:

- Is the building less than a year old, or has any area been renovated, redecorated or newly furnished within the past month?
- Are suitable cleaning products being employed? Is time of use optimum, so as to reduce exposure of occupants?
- Do any activities involve the use of large amounts of chemicals, especially highly volatile solvents? Are solvent odours present? Are soaked materials and solvents being disposed of properly?
- Is extra ventilation or a separate ventilation system being used where there are localized sources? Is the ventilation system recirculating VOCs from a source throughout the building?

5.2.7.4 Measurement Methods and Equipment. Suitable control and test locations are identified from results of the preliminary assessment. The assumptions and analytical methods used should be clearly stated when reporting VOC results.

a. Direct-reading tubes

Direct-reading tubes contain chemicals that react with certain individual VOCs to produce a colour change. A fixed volume of air is drawn through the tube by means of a hand pump. The length of stain observed is proportional to the volume of air sampled and the concentration of VOCs. The method was developed for the industrial environment and is only marginally suitable for use in the office environment because of the much lower VOC concentrations usually found there. The method may, however, be useful for screening purposes. Sensitivities are in the parts per million range.

b. Passive badges

Passive organic vapour samplers are available with sensitivity levels in the range of sub-parts per million. These samplers employ charcoal or another medium as an adsorbent and use sampling periods of 8 hours to 1 week. The sampler is sent to a laboratory for analysis and provides average concentration.

c. Photoionization detectors

Photoionization detectors (PIDs) are direct-reading instruments that detect airborne chemicals by first breaking them into electrically charged fragments by means of an ultraviolet (UV) lamp, then detecting the fragments (ions) on a metal screen. The number of VOCs that can be detected increases as the lamp's UV energy increases: 11.7 electron volt is the highest energy commonly available and the most suitable for offices. Note that identification of the individual chemicals present is not possible.

Responses have been measured for a number of chemicals commonly found in office air. As they vary quite widely, detector accuracy is probably no better than 50% when measuring TVOC. Toluene is recommended for use as the calibration gas, as it has an intermediate response.

PIDs are very useful screening devices and can identify source locations and pollution migration routes.

d. Flame ionization detectors

In the flame ionization detector (FID) method of measuring TVOC, chemicals in air are burned to produce ionized products that generate a current in proportion to the concentration. The ionization process is non-specific, and the result is displayed in real time.

Like PIDs, FIDs are useful for qualitative survey work, such as source location during a walkthrough and the identification of sampling points. The variability in response is much less for the FID than for the PID. Also, a greater number of VOCs are detected by the FID method.

Several instruments combine a FID for screening with a portable gas chromatography (GC) unit for more detailed analysis and specific compound quantitation.

e. Infrared detectors

Infrared detectors are direct-reading instruments suitable for monitoring individual VOCs. The variable-wavelength models can be adjusted to scan for several different VOCs.

The sensitivity is in the parts per million and sub-parts per million range but is not as good as that of a GC, and there can be a problem with interferences when several VOCs are present together.

Direct-reading instruments such as PID, FID, and infrared detectors can be operated over several hours or several days with chart recorders and external or internal data loggers to yield concentration profiles over time.

f. Active sorption/chemical analysis

Active sorption methods employ tubes packed with a sorbent that traps the VOCs when air is pumped through the tubes. Sorbents include organic polymer resins, such as Tenax, XAD, or activated charcoal. The analysis yields information on the type and quantity of chemicals present.

In *charcoal tube sampling with solvent extraction*, charcoal tubes are used with battery-operated sampling pumps, and the VOCs collected are extracted with solvent, usually carbon disulphide. Either GC or GC with mass spectrometry (MS) is used for the analysis. The GC/MS gives more detailed information for identification of chemicals present.

Charcoal tubes demonstrate nearly 100% accuracy in detecting non-polar hydrocarbon and chlorinated hydrocarbon solvents with boiling points in the range of 50-200ºC. However, some chemicals (those that tend to dissolve in water rather than in solvent, such as ammonia and darkroom chemicals) are not well trapped or extracted and are detected with low efficiency. An additional problem with this method is that VOCs are measured individually, so one must total the individual measurements to calculate TVOC. Where complex mixtures of chemicals are present (e.g., liquid-process photocopier solvent), this method underestimates TVOC, because many of the chemicals are present in quantities too small to be measured.

Multi-sorbent sampling with thermal desorption seeks to improve on the charcoal tube method in three ways:

- Using tubes containing three adsorbents extends the trapping range of the tubes to a wider boiling point range.

- Thermal desorption is used to transfer the VOCs from the tube to a GC or a GC/MS. This increases the number of VOCs detected, because only chemicals in the charcoal tube that dissolve in the solvent during solvent extraction will be transferred.

- The sample is split, and part goes directly to a FID that detects all the chemicals in the sample regardless of the type and quantity present. This gives a better measure of TVOC than the charcoal tube method. The remainder of the sample is analysed by a GC or GC/MS in the usual way to provide identification.

A variety of other adsorbent tubes exists, using both solvent extraction and thermal desorption. For example, there are tubes specifically prepared for collecting dioxins or polychlorinated biphenyls (PCBs). It is also possible to measure individual chemical concentrations using thermal desorption.

5.2.7.5 Strategy for Remediation. Measures to control VOC emissions include selection of materials with low emission rates, and increased ventilation during the first 3 months of occupancy in new or retrofitted buildings.

Chemical emissions occurring as a result of occupant or maintenance activities should be counteracted. Courses of action include:

- increasing outside air levels to dilute concentrations if the source is weak (e.g., emissions from new furnishings)

- storing paints, cleaners, and solvents in areas with separate exhaust and not in the mechanical room

- choosing dry process copiers over wet copiers if many copiers are used in the building

- installing local exhaust for print machines and photographic darkrooms.

5.2.8 Microbials

In indoor air, microbial contamination can be a serious problem. High humidity, reduced ventilation, tighter buildings, and HVAC systems that have water or condensation (humidifiers, cooling coils, etc.) allow for the growth and distribution of various microbials. This is a matter of concern because of the various associated human health and comfort implications.

A wide variety of microbials (micro-organisms) such as fungi (moulds, yeasts), bacteria, viruses, and amoebae can be found in the indoor environment. Contamination of indoor air with micro-organisms can occur under many circumstances. Such contamination most often occurs when a fault in the building, HVAC, or other system allows the proliferation of micro-organisms.

Viruses and bacteria cause diseases, but indoor air is not usually the cause of the viral infection (e.g., common cold). Viruses do not survive long outside the host, and transmission depends on contact with an infected individual. Bacteria such as *Legionella* and related species can, however, be a significant IAQ concern. Legionnaire's disease is an infection that can result in pneumonia if it is disseminated from an amplification site to the breathing zone of a susceptible host. Cooling towers, evaporative condensers, and hot water systems can be amplification sites for *Legionella* and can disseminate aerosols containing the bacteria into the indoor air. Endotoxin-producing bacteria can also occur in some kinds of humidification systems.

Inhalation of very large concentrations of fungal spores can cause hypersensitivity pneumonitis, but this rarely results from building exposure. Chronic exposure to most fungi can induce allergic or asthmatic reactions in humans, and a very few species can cause diseases directly. Some moulds are "toxigenic," producing mycotoxins that often accumulate in the spores. The inhalation of spores containing certain mycotoxins has been shown to induce many of the symptoms normally associated with SBS.

Other products of fungi include certain VOCs. Such compounds (characterized by mouldy smells) occur only when there is active and considerable fungal growth. There is some evidence to suggest that these can contribute to SBS.

It is important to remember that some individuals (AIDS patients and immuno-compromised individuals, such as those on chemotherapy) are very susceptible to certain microbial exposures.

5.2.8.1 Background. Microbial evaluation of indoor air started in the late 1950s, when secondary (nosocomial) infections of patients became a major concern in many hospitals. One cause was airborne micro-organisms spread via ventilation systems.

In Europe and North America, there have been reports of a number of building-associated outbreaks of influenza-like illness ("humidifier fever"), in which affected individuals manifest symptoms such as malaise, fever, shortness of breath, cough, and muscle aches. These illnesses usually occur as an acute response to microbial antigens aerosolized from contaminated HVAC system components or from other building components that may have been damaged by recurrent floods or moisture problems. Various respiratory illnesses have been reported from building-related fungal exposure. Affected individuals often experience relief when they leave the building for several days.

Fungal spores, especially *Cladosporium* and *Alternaria*, are common in outdoor air during the growing season, and the principal fungi that grow on leaves constitute 60-70% of the spores in air. These fungi can induce allergies, but most people are not particularly affected.

Species of fungi that have the physiological ability to grow and accumulate indoors or in air handling equipment are quite different from the common plant and leaf fungi. Condensation and water accumulation allow the growth of many fungi that can induce allergies and other health problems not readily detected with current medical procedures.

The presence of micro-organisms in the indoor environment in sufficient numbers or kinds to cause health or comfort problems is dependent on a number of factors. Fungal spores are ubiquitous because they reside in the soil. HVAC systems are complex and offer a number of environments where microbial populations may flourish. Water spray humidifiers containing stagnant water, filters packed with organic dusts, cooling system condensate pans, and interiors characterized by excessive humidity may all offer suitable environments for microbial proliferation under appropriate circumstances. In large buildings, the HVAC system will serve to transport micro-organisms from the locus of contamination to the vicinity of the occupants.

Aspergillus fumigatus, Histoplasma capsulatum, and some other fungi can cause certain diseases. Although this is rare in urban environments, buildings exposed to quantities of bird or bat droppings are at risk. Roosts in or near air intakes need to be eliminated. Older buildings and vacant properties having bird or bat infestations should be retrofitted or demolished with caution.

5.2.8.2 Checklist. In a walkthrough, possible microbial reservoirs and amplification sites should be determined:

- air intakes, filter units, cooling/heating fans and coils, spray humidifiers, reservoirs, ducts, insulation, induction and fan coil units, drain and condensate pans and sumps that are either dirty or wet

- mouldy, damp odours, evidence of a previous flood or water leak
- portable humidifiers and water coolers containing slime or algae
- mouldy, dirty or wet ceiling tiles, plaster/gyprock, carpet, window sills/frames.

Remedial action should be carried out in problem areas as soon as possible.

5.2.8.3 Measurement Methods and Equipment. The variety of microbial organisms in the air is enormous; some exist as viable particulates, others are non-viable and include dead spores, toxins, and submicron particulates. Although active fungal growth requires water, release of fungal spores into air can take place for months after the water has disappeared. Air sampling is undertaken in order to recognize and control microbial air contamination and as a means of quantitative and qualitative monitoring. Air sampling is not an infallible means of reliably determining microbial contamination, and caution must be used in interpreting the results.

Identification of the fungal species is critical for a complete determination of whether an abnormal or hazardous condition exists. This process requires a mycologist with expertise in IAQ. Excessive numbers of fungal propagules or modest numbers of certain disease-causing or toxigenic fungi can result in health or comfort problems. When fungi are growing in or on building surfaces or systems, removal is necessary.

Quantities of fungi have been assessed traditionally by the measure "colony-forming units" per cubic metre (CFU/m^3) of air, measured by collecting spores and allowing them to grow on some type of agar medium. This method can be described as semi-quantitative, as there are difficulties in collecting spores that have different shapes, sizes, and masses. In addition, all media are selective to some extent. Further, some fungi produce fewer propagules than others for a given amount of fungal biomass/activity. The spores of some species rapidly become non-viable but can still pose a problem. The number of propagules in indoor air is highly variable and is a function of many factors, such as the activity in the room, the operation of the HVAC system, weather conditions, wind speed, and the microbial life-cycle. Research is in progress on these issues.

Sampling instruments include single or multi-stage impactor and centrifugal samplers from various manufacturers. Spore concentrations in buildings have been shown to vary over an order of magnitude in less than 1 minute. Similarly, recoveries of fungal species have been shown to be directly correlated with sampling time.

Samples should be taken while the HVAC system is operating normally. Early Monday morning may be a good time if the HVAC system has been turned off for the weekend. Samples should be taken at several locations throughout the area, including near air outlets, at desk level, and in the adjacent area. In addition, potential source locations in the mechanical equipment room should be sampled, including the air supply plenum after the humidifier and at the outside air intake.

Surface samples should be taken with sterile swabs (e.g., autoclaved, moistened cotton wool swabs individually packed in tubes) on the surfaces of diffusers, fan blades, coils, pans, and humidifiers. The samples are plated on a suitable agar medium containing antibiotics. This method is used to determine possible sources of contamination.

5.2.8.4 Interpretation of Results. Since 1989, the ACGIH Bioaerosols Committee has recommended rank order assessment as a means of interpreting air sampling data. This interpretation has been part of the practice in Government of Canada investigations since 1986. The presence of one or more species of fungi indoors, but not outdoors, suggests the presence of an amplifier in the building. Species identification is critical to the analysis. Because of the problems noted above, numerical guidelines cannot be used as the primary determinant of whether there is a problem. However, numerical data are useful under defined circumstances.

Information from a large data set obtained by experienced individuals using the same instrument has practical value. Investigations of more than 110 federal government buildings over several years has resulted in the creation of such a data set. Fungal data from about 3000 samples taken between 1986 and 1995 with a Reuter centrifugal sampler with a 4-minute sampling time have been used to prepare the following interpretation notes. Data acquired with other samplers require similar analysis. However, if a 4-minute sampling time is used, the numerical data from any proprietary sampler will probably be comparable.

- Significant numbers of certain pathogenic fungi should not be present in indoor air (e.g., *Aspergillus fumigatus*, *Histoplasma* and *Cryptococcus*). Bird or bat droppings near air intakes, in ducts or buildings should be assumed to contain these pathogens. Action should be taken accordingly. Some of these species cannot be measured by air sampling techniques.

- The persistent presence of significant numbers of toxigenic fungi (e.g., *Stachybotrys atra*, *toxigenic Aspergillus*, *Penicillium* and *Fusarium* species) indicates that further investigation and action should be taken accordingly.

- The confirmed presence of one or more fungal species occurring as a significant percentage of a sample in indoor air samples and not similarly present in concurrent outdoor samples is evidence of a fungal amplifier. Appropriate action should be taken.

- The "normal" air mycoflora is qualitatively similar and quantitatively lower than that of outdoor air. In federal government buildings, the 3-year average has been approximately 40 CFU/m^3 for *Cladosporium*, *Alternaria*, and non-sporulating basidiomycetes.

- More than 50 CFU/m^3 of a single species (other than *Cladosporium* or *Alternaria*) may be reason for concern present. Further investigation is necessary.

- Up to 150 CFU/m^3 is acceptable if there is a mixture of species reflective of the outdoor air spores. Higher counts suggest dirty or low efficiency air filters or other problems.

- Up to 500 CFU/m^3 is acceptable in summer if the species present are primarily *Cladosporium* or other tree and leaf fungi. Values higher than this may indicate failure of the filters or contamination in the building.

- The visible presence of fungi in humidifiers and on ducts, mouldy ceiling tiles and other surfaces requires investigation and remedial action regardless of the airborne spore load.

- There are certain kinds of fungal contamination not readily detectable by the methods discussed in this report. If unexplained SBS symptoms persist, consideration should be given to collecting dust samples with a vacuum cleaner and having them analysed for fungal species.

5.2.8.5 Strategy for Remediation. The principal guideline for microbial control is to keep fungal growth in buildings to a minimum. This can be accomplished in a number of ways:

- Remove water sources that encourage fungal growth. Prevent the accumulation of stagnant water in and around HVAC system mechanical components, such as under the cooling coils of AHUs. Maintain the relative humidity of indoor spaces at less than 60%. Repair all external and internal leaks promptly and permanently.

- Remove fungus-contaminated substrates. Remove and discard porous organic materials that are obviously contaminated (e.g., mouldy ceiling tiles, mildewed carpets). Wash all smooth surfaces that have been contaminated by fungi with diluted 5% bleach (250 mL/4 L water).

- In HVAC systems, use steam for humidification rather than recirculated water. Spray humidifiers where feasible. If spray systems are used, a rigorous preventive maintenance program must be employed, as these systems can easily become contaminated with bacteria and fungi. This includes maintenance of slime-free surfaces and the addition of potable water to the reservoir. Humidifiers should be drained and cleaned with chlorine bleach at intervals of 2-4 months. Rust and scale deposits should be removed from HVAC system components once or twice a year. HVAC systems should be turned off during cleaning operations, which should be scheduled during weekends and unoccupied periods.

- Porous synthetic insulation is often used to line ducts and air handling and induction units. The vapour barrier on fibreglass should be intact. There should be no standing water or condensation on these surfaces. Dirty, contaminated insulation should be removed, as the effectiveness of cleaning or encapsulation has not yet been verified.

- Personal portable humidifiers should not be allowed in offices, as they are seldom maintained properly and can easily become contaminated.

- The use of efficient filters to control the load of spores entering the air handling system is important. Use prefilters and extended surface-type secondary filters with dust-spot efficiency ratings higher than 85% when possible. Replace the filters at regular intervals. The prefilters are normally changed 4-6 times a year and secondary bag filters once a year, depending on outside conditions and retrofit activity.

5.3 Assessing the HVAC System

The HVAC system should be providing adequate amounts of outdoor air based on occupancy rates and activities (ASHRAE Standards). The minimum ventilation rate should be maintained continuously during the occupancy period: the amount of outdoor air volume should never drop below 7.5 L/s per person, and offices should receive 10 L/s per person.

IAQ complaints can often be linked to insufficient ventilation. Ventilation systems can also introduce outdoor contaminants and transport pollutants within the building. Every component of the HVAC system is of interest, either as a source of contamination or as a component that fails to provide a necessary air handling or air conditioning function. The procedures described below constitute current good practice.

5.3.1 Collecting Background Information

- Talk to facilities staff. Find out about equipment operating and maintenance schedules. Maintenance that dislodges or generates pollutants should be performed outside the usual building occupancy periods. Discussions may reveal patterns that relate the timing of complaints to cycles of operation or to other events. A log of maintenance activities and system operations can be helpful.
- Review documentation on HVAC design, installation, and operation. Consider:
  - the design capacity, supply and exhaust air volume
  - the existing and planned use of each building area
  - the location of internal AHUs and supply and return diffusers serving the complaint area.
- Compare actual flow rates, distribution, and outdoor air rates with design values.

5.3.2 Inspecting the HVAC System

- Inspect outside air dampers, noting their position, the type of control mechanism, and its condition.
- Note the distance and direction of combustion sources, building exhausts, cooling towers, and other potential sources of pollutants in relation to the outside air intake.
- Examine the garage and loading dock for proper ventilation and pollution migration.
- Check supply air fans for operational problems, including defective belts, missing blades, build-up of particulates, and microbial growth.
- Check the interior of the mixing chambers for signs of failing insulation, debris, rust, or microbial growth.
- Ensure that air ducts and ceiling plenums are being maintained and cleaned to prevent dust from providing a substrate for mould growth.
- Verify the existence of a proper maintenance schedule for ceiling AHUs and perimeter fan coil units, induction units, and unit ventilators.
- Check that all combustion sources are being exhausted.
- Ensure that the efficiency rate of the filter bank is at least 30% (dust spot). In large office buildings, a primary filter – usually a panel or roll type – is used in conjunction with a higher efficiency (up to 85%, dust spot) bag filter. A maintenance schedule should be in place. Examine the system filters for proper fit. Verify that they are replaced often enough to prevent build-up of particulate matter. Filters should be replaced when the specified maximum pressure drop is reached.
- Check the system for microbial growth:
  - Note the presence of stagnant water. Condensate pans under cooling coils should have drain lines and sufficient pitch so that water drains completely.

- Verify the existence of a maintenance program to prevent the build-up of microbial slime on HVAC system components that become wet. Contaminated surfaces should be disinfected while the building is vacant. Approved biocides should be used in water spray humidifiers as a decontamination procedure only if proper cleaning cannot be done.
- Monitor the general bacterial population in humidifier reservoirs and water towers by taking samples using test strips or slides (heterotrophic plate counts) and comparing the results with a colour chart to determine concentration.
- Examine the humidifier for the presence of microbial growth, particulates, or chalky deposits and note any use of treatment chemicals. Water quality is best maintained by adding potable water to the reservoir so that the level of total dissolved solids does not exceed 2-3 times its normal concentration.
- Central boiler steam should not be injected directly into the supply air by a steam humidifier because of the potentially harmful volatile chemicals used to treat the boiler supply water. A steam-to-steam converter or a separate steam generator should be used.

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