NRC·CNRC Institute for Research in Construction
CNRC·NRC Institut de recherche en construction

http://irc.nrc-cnrc.gc.ca

National Research Council Canada

Managing Volatile Organic Compounds and Indoor Air Quality in Office Buildings – An Engineering Approach

RR-205

Shaw, C.Y.; Won, D.;Reardon, J.

March 2005

A version of this document is published in / Une version de ce document se trouve dans:
Final Report 5.2 – CMEIAQ-II: Consortium for Material Emission and IAQ Modelling II

National Research Council Canada
Conseil national de recherches Canada

Canada

Consortium for Material Emissions and Indoor Air Quality Modelling II (CMEIAQ-II)

In 2000, the Institute for Research in Construction, National Research Council Canada (IRC/NRC) launched the second phase of the Material Emissions and Indoor Air Quality Modelling project (CMEIAQ-II). The second phase of this project is the direct result of the support and suggestions from the first phase's consortium members for continued work on this research topic. In the second phase, the research is directed towards two principal objectives. The first is to develop the knowledge and tools needed to estimate concentrations of volatile organic compounds (VOCs) generated by the emissions from building materials and furnishings in order to gain a better understanding of the effects of those products on indoor air quality (IAQ). The second is to provide the scientific bases needed to enhance indoor air quality guidelines for office and residential buildings. An important addition to the project in this phase was the Health and End Users Advisory Committee, which was tasked to provide much needed input from the health sector and advice to help tailor the project outputs to better meet the needs of end-users.

Phase II Tasks

The specific tasks of the phase II research were:

- To assemble a target VOC list on which to focus our efforts for the analysis of the emission test results. The list includes chemicals which are known to be emitted from various materials, and, especially, chemicals known to have health effects;
- To determine the ranges of variation of the emissions from selected materials, which may result from material variability or environmental influences;
- To expand the database to include a total of 69 materials, and to re-analyze the existing data to cover as many VOCs on the new target list as possible;
- To refine the Material Emission DataBase and Indoor Air Quality (MEDB-IAQ) simulation program to make it more user-friendly;
- To develop and validate empirical and mass-transfer based source models; and
- To develop a best practice guide for managing VOCs/IAQ in office buildings.

Significance of the Project

A recent report by a multidisciplinary group of European scientists (EUROVEN) based on existing and limited literature, recommends that outdoor air supply rates need to be increased to 30 L/s per person from the current ASHRAE recommendation of 10 L/s per person to improve indoor air quality for health, comfort, and productivity concerns. On the other hand, a previous NRC experimental study indicates that increasing the ventilation rate to speed up the removal of air-borne VOCs, even when energy use is not a concern, is not effective. The most efficient strategy to maintain indoor air quality is to remove the contaminants at the source (source control) and then to rely on ventilation (dilution) to remove the air-borne VOCs.

This research contributes to improved indoor air quality by developing knowledge and tools for effectively applying source control to reduce ventilation needs (and hence, save energy). The work provides the relative contribution by a given product to up to 90 VOC concentrations (some of which are known to have adverse health effects), allowing intelligent, informed choices of building materials and indoor consumer products. Product manufacturers will benefit by learning how their products can be improved with respect to VOC emissions, and where their products stand relative to others in simulations of their actual use. The information collected in Phase II will also make it easier for investigators to diagnose possible IAQ problems in buildings, and explore trade-offs between increased ventilation and source control.

The consortium for Phase II (which has a Steering Committee, a Technical Advisory Committee, and a Health & End Users Advisory Committee) was established to set the research priorities and help fund the project. Members of the consortium include: Public Works & Government Services Canada, Natural Resources Canada, Canada Mortgage and Housing Corporation, Health Canada and the National Research Council. In addition, the following organizations have made significant in-kind contributions to the consortium project through close research collaboration with the IRC/NRC project team: Canadian Composite Panel Association, Carleton University, Chemical Manufactures Association (Rohm & Haas), Dalhousie University, Gypsum Board Association, Saskatchewan Research Council, Syracuse University, University of Calgary, University of Miami, U.S. Environmental Protection Agency (EPA), U.S. National Institute of Standards and Technology (NIST), and Virginia Polytechnic Institute & State University.

The CMEIAQ-II final research reports include:

Report 1.1	Target VOC list
Report 1.2	Methodology for Analysis of VOCs in Emission Testing of Building Materials
Report 2.1	Specimen Variability: A Case Study
Report 2.2	Effects of Environmental Factors on VOC Emissions from a Wet Material
Report 2.3	Effects of Material Temperature on VOC Emissions from a Dry Building Material
Report 3.1	Material Emission Data: Small Environmental Chamber Tests
Report 3.2	MEDB-IAQ Version 4.1 Beta
Report 4.1	Model Development for VOC Emissions from Wet Building Materials
Report 4.2	Validation of a Mass-transfer Model for VOC Emissions from Wet Building Materials
Report 4.3	Validation of Empirical Models with Long-term Emission Testing Data
Report 5.1	Indoor Air Quality Guidelines and Standards
Report 5.2	Managing VOCs and Indoor Air Quality in Office Buildings: An Engineering Approach

Reports 1.1 and 1.2 provide the information on the Target VOC list and the analysis method for the VOCs on the list. Reports 2.1 and 2.2 present research outcomes on both inherent and environmental factors inducing variability in material emissions. Report 2.3 discusses VOC emissions as a function of surface temperatures, which can be applied to emissions from a radiant floor heating system. Report 3.1 provides material emission testing data and the resulting coefficients for empirical emission models for the expansion of MEDB-IAQ simulation software. Report 3.2 is a user manual for the revised MEDB-IAQ. Reports 4.1 and 4.2 deal with the development of a mass-transfer based model for wet building materials and the validation of the model with experimental data. Report 4.3 compares empirical models based on short-term emission testing data with those based on long-term data. Report 5.1 contains summaries of existing guidelines and standards associated with indoor air quality. Report 5.2 is a manual for property managers and building operators for their duties in managing VOCs in office buildings.

Managing Volatile Organic Compounds and Indoor Air Quality in Office Buildings: An Engineering Approach

Summary

There is a growing awareness of the importance of maintaining good indoor environments, and, with that awareness, a growing need to understand the parameters that contribute to a building's indoor air quality (IAQ) and the effect of IAQ on occupant well-being. This report gives a brief overview of various parameters affecting IAQ. It also provides some practical recommendations for maintaining good IAQ with a focus on minimizing the airborne concentrations of volatile organic compounds (VOCs) in buildings.

This report is intended for use mainly by building owners, property managers, and building operators. It covers the following topics:

- parameters affecting indoor environments,
- VOCs and their sources,
- main causes of occupant complaints,
- VOCs emitted from office furniture and their concentrations in buildings,
- proactive plans for minimizing VOC effects,
- diagnostic techniques for identifying potential IAQ and ventilation problems,
- the balance between acceptable IAQ and energy use, and
- best practices for managing IAQ/VOCs in buildings.

A brief summary of the main recommendations for managing VOCs in buildings is given below.

- Use low-emitting building materials/products.
- During renovation, seal the affected area and vent the space through leeward side windows (summer only), a smoke shaft, or stair shafts with open outside door at the roof level. Use portable exhaust fans to assist venting.
- Immediately after renovation, operate the HVAC system with a ventilation rate of up to 20 L/s/person (40 cfm), depending upon the system capacity and outdoor air temperature (watching closely for warnings of coil freezing) for two to four weeks.
- Avoid contaminated ventilation air by locating air intakes as high as possible in the building and away from pollution sources such as cooling towers and exhaust outlets.
- Provide designated exhaust for localized emission sources.
- Take advantage of free-cooling, weather permitting.
- Control ventilation rates using occupant-generated CO_2 , if feasible.
- Develop a preventative maintenance manual including:
  - preventative maintenance procedures and schedules for implementation,
  - calibration instructions and schedules for various sensors,

  - HVAC fault identification and location procedures, and
  - equipment information such as warranty coverage and manufacturer's help hotlines.
- Develop a proactive program for managing IAQ/VOCs by conducting an annual walk-through building inspection. During which:
  - pay attention to inadequate airflow from supply air diffusers, locations of air intake, drafts, noise, glare on VDTs, odours, and wet surfaces.
  - if feasible, measure concentrations of CO_2 and TVOC.
- Consult technical personnel if the levels of CO_2 and TVOC exceed 800 ppm and 2.5 mg/m^3, respectively. (Note: occupant complaints may occur at lower levels, i.e., 600 ppm CO_2 and/or 1.0 mg/m^3 TVOC.)

Table of Contents

List of Figures

List of Tables

Managing Volatile Organic Compounds/Indoor Air Quality in Office Buildings: An Engineering Approach

Introduction

Occupant health, comfort, and productivity are primary considerations for commercial building owners and operators, because occupants' salaries dominate the life cycle cost of such buildings. There is strong theoretical evidence, although limited data, indicating that improvements to indoor environments can result in significant improvements to health and productivity. Estimates of potential annual savings plus productivity gains in the USA are between $30 and $170 billion with benefits outweighing costs by a factor ranging from 18 to 47.

Acceptable and cost-effective indoor environments depend on the performance of building systems that control noise, heating, cooling, material off-gassing, ventilation and illumination. These systems must be properly designed and maintained in order to provide continuing comfort, air quality, and operating economy. To achieve this, in addition to physical factors such as temperature, air distribution, and relative humidity, it is necessary to understand occupants' reactions to their indoor environments and the effects of environmental, human, and organizational factors on their productivity. Also, as pressures continue to reduce greenhouse gas emissions, the energy efficiency of building systems that support the indoor environment also needs to be addressed. An integral approach that addresses heating, ventilating, air-conditioning, noise, lighting, material emissions, energy, and human and organizational aspects in a systematic manner is needed to design and maintain a satisfactory indoor environment at a minimal cost.

Since the early 1980s, the Institute for Research in Construction has conducted several multi-year studies, including the phase I and phase II of the Material Emissions and Indoor Air Quality Modelling projects, to systematically address the impacts of the aforementioned factors on indoor environments and occupant satisfaction. While the results of these studies have been communicated to the scientific community, little effort has been made to transfer the findings in a manner appropriate for use by building owners, property managers, and building engineers, who are the end users of the results. To fill the apparent information gap, a special working group was established under the Health and End Users Advisory Committee of the Material Emissions and Indoor Air Quality Modelling project (Phase II). The main objective of this working group was to bring together building researchers, building owners and managers, and health officials to review past and current research findings related particularly to source control and ventilation, and to disseminate it in a manner that can be readily used by building practitioners.

This report is the product of the working group. It consists of three parts. Part I presents background information required to answer occupants' questions about indoor air quality and health. Part II provides the information required to identify potential IAQ problems and assess the IAQ level in buildings. It also presents some evidence supporting the recommendations for managing buildings. Part III lists best practices for managing IAQ in buildings. While the report focuses primarily on office buildings, the resulting technologies and expertise are also applicable to other types of non-industrial buildings, such as multi-family residential buildings, schools and hospitals, to solve specific problems and improve indoor air quality.

Part I – Background Information

This part of the report contains information that can be used by building owners, managers, and engineers when answering indoor air quality related questions from the occupants of their buildings. A main focus of the discussion is on volatile organic compounds (VOCs), their sources and potential health effects.

Indoor Environment (IE) and Indoor Air Quality (IAQ)

The conditions of indoor environments are affected by three main physical factors: noise, lighting, and IAQ. In addition, occupants' perceptions of their environments may also be affected by many other factors including job stress and satisfaction. Furthermore, a good and practical design to achieve an acceptable indoor environment has to consider additional factors such as costs, health and safety.

Of all the IE related problems, the most familiar and least understood one is IAQ. IAQ is closely related to thermal comfort, ventilation, indoor contaminants, and material emissions. It is primarily controlled by the design and operation of HVAC systems and the selection of building materials and furnishings. Even though IAQ is not directly related to noise, lighting, and human factors, stuffy air or poor air quality has been frequently used by occupants to express their dissatisfaction with the noise level, poor lighting, and, sometimes, career development and well-being. To effectively address occupants' complaints, it is necessary to remember that not all complaints are caused by poor IAQ.

Common Causes of IAQ Problems

The main causes of IAQ problems are inadequate ventilation and indoor contaminants. Poor lighting, noise, and human and organizational factors (e.g., job stress, job satisfaction, and personal problems) can also lead to occupants' complaints. This type of complaint is known as a perceived IAQ problem, and should be addressed together with appropriate experts.

Inadequate ventilation is usually the result of inadequate ventilation rate (for office buildings, the recommended ventilation rate is 20 cfm or 10 L/s per person), poor ventilation air distribution, or both. Indoor air contaminants have many sources including building materials and furnishings, occupant activities, and building HVAC systems. Major indoor air contaminants are:

- allergens, such as house dust, pet dander, etc.,
- inorganic gaseous contaminants, such as CO, CO_2, ozone, SO_2, nitrogen dioxide, etc.,
- non-viable particulate matter including biological debris and asbestos,

- viable particulate matter such as moulds and spores,
- radon, and
- VOCs.

Volatile Organic Compounds (VOCs)

VOCs include a large group of contaminants that are of particular concern when addressing IAQ issues. VOCs are chemical compounds that are gaseous at room temperature and contain, at least, one carbon atom and one hydrogen atom. Formaldehyde is a VOC but is often treated separately from other VOCs because it is not detected by the gas chromatographic methods commonly used to measure VOCs.

VOCs can be grouped into three classes based on their boiling points (Yu and Crump, 1998):

- very volatile organic compounds (VVOCS); boiling point range: 0^oC to $50\text{-}100^oC$,
- volatile organic compounds (VOCs); boiling point range: $50\text{-}100^oC$ to $240\text{-}260^oC$,
- semi-volatile organic compounds (SVOCs); boiling point range: $240\text{-}260\,^oC$ to $380\text{-}400\,^oC$.

Typical VOC Sources

Typical VOC sources include building materials and furnishings, occupant activities, cleaning agents and office machines. Some sources, such as glues used for carpet and wallpapers, are not obvious. Contaminants generated outdoors can also get into a building through the outdoor air intakes. The HVAC system itself may be a source of VOCs. The most common sources of odorous VOCs are air filters and ducts.

Potential Effects of VOCs on Health and Well-being

It appears that there is no well-substantiated evidence linking a large number of individual VOCs found in the indoor air to health concerns, particularly for occupants with normal health. An article prepared by the Institute for Environment and Health states that "the majority of individual VOCs that make up the spectrum of VOCs found in the air of UK homes has no reported health effects, even at levels orders of magnitude higher than those generally found in homes. These VOCs include aliphatic hydro carbons such as undecane, most aromatic hydrocarbons such as toluene, esters and alcohols" (MRC IEH, 1999). Unless there are special contamination sources, it is expected that this statement might apply equally well to Canadian homes and offices.

However, some VOCs detected in the indoor air are recognized carcinogens. Formaldehyde, for example, is one of them. It is a colourless gas. At a concentration of 1 ppm a pungent odour can be detectable. Health Canada's current exposure guidelines for formaldehyde in residential indoor air (guidelines for office buildings are not yet available) consist of an Action Level of 120 $\mu g/m^3$ or 0.10 ppm and a Target Level of 60 $\mu g/m^3$ or 0.05 ppm (HC, 1989). These levels were under review by Health Canada at the time of writing. There are also reports that exposure to other VOCs have led to symptoms varying from headache, nausea, dizziness, eye, skin, and throat irritations, and sensory irritation to general discomfort (Jones, 1999). The odour associated with some VOCs may also cause complaints.

Some individuals, especially those who suffer from asthma and environmental hypersensitivity, are more susceptible than persons with normal health. Recently, there has been an increased number of IAQ conferences at which the attendees are asked to refrain from using perfume or deodorant. There is also increased concern for the long-term health effects of various combinations of VOCs, each present at a very low level.

For office buildings, the term "Sick Building Syndrome" (SBS) has been frequently used to describe the IAQ-related complaints by office workers. SBS appeared to be first used by the members of a WHO Working Group in their report entitled "Indoor air pollutants: Exposures and Health Effects" (WHO, 1983). Common symptoms of SBS include headache, nausea, nasal congestion, mucous membrane irritations of nose, eyes and throat, fatigue, and less frequently, dry or itchy skin. SBS is characterized by its rapid disappearance of symptoms, within minutes to hours, after leaving the building. SBS is distinguished from more medically serious building-related illness (BRI) in that the reported symptoms are not clinically verifiable. Also, BRI is usually accompanied by SBS complaints among co-workers. A random survey indicated that about one-quarter of US office workers perceived to have IAQ problems in their offices and 20% of all respondents believed that their performance was hampered by poor IAQ (Woods, 1989).

Levels of VOCs in Buildings

Since the 1980s, IRC has conducted several studies to measure the VOC concentrations in various types of buildings. IRC has also undertaken two multi-year projects on material emissions. A brief summary of the results is reported below.

VOC Emissions from an Office Workstation

Office furniture can emit a large number of VOCs. A series of tests were conducted in a full-scale stainless steel chamber (5 m x 4 m x 2.75 m high) to determine the emission source and sink characteristics of an office workstation furniture system under conditions commonly maintained in office buildings (Zhang et al., 1997). During the test, the chamber was maintained at 23 ºC, 50% RH, and 5 ac/h supply air rate including 0.5 ac/h ventilation (outdoor air supply) rate. Emissions of a total of 45 VOCs were identified (listed in Table 1).

Table 1. VOCs emitted from the office workstation

Aliphatic Hydrocarbons	Butane; Pentane; alpha-Pinene; Decane; Limonene; Branched C11; Undecane; Branched C12; Dodecane; Derivative of neoprene; Hexadecane.
Aromatic Hydrocarbons	Benzene; Toluene; Ethylbenzene; o-, m-, p -Xylene; Styrene; Propylbenzene; Trimethylbenzenes; 4-Phenylcyclohexene (4-PC).
Aldehydes	Pentanal; Hexanal; Heptanal; Octanal; Nonanal; (E)-2-Nonenal; Decanal.
Ketones	Acetone; 2-Butanone; Acetophenone.
Chlorinated Hydrocarbons	Trichloromonofluoromethane; Methylene Chloride; 1,4-dichlorobenzene.
Alcohol	Methanol; Ethanol; Isopropanol; 2-butoxy-ethanol; Undecanol.
Others	Carbon disulfide; Acetic Acid; Propanoic acid, 3-ethoxy-, ethyl ester; Phenol; 2,6-t-Butylo, p-chinon; Butylated Hydroxytoluene (BHT).

Of the 45 VOCs, the six most abundant compounds were: nonanal, phenol, toluene, isopropanol, pentane, and acetone. Figure 1 shows the emission rates of the TVOC and these six most abundant VOCs. As shown, at a constant ventilation rate, after reaching its peak value, the concentration of each VOC decreased rapidly for about 10 hours and became relatively constant afterwards.

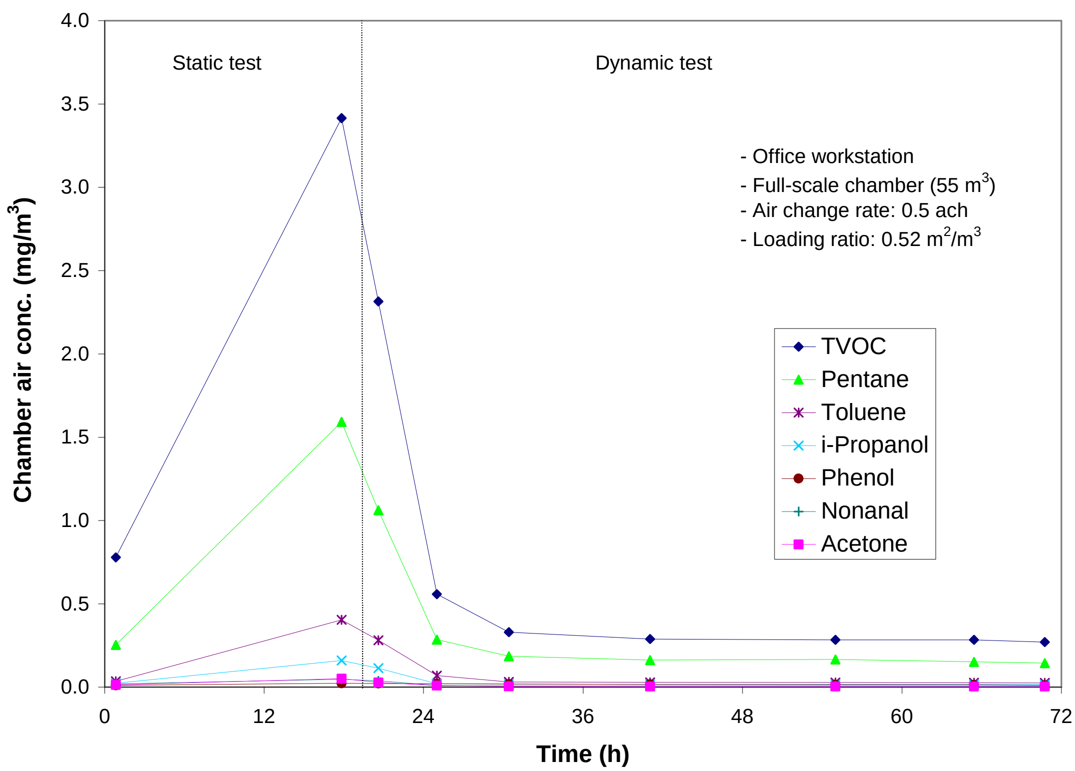

Figure 1. Measured concentrations of TVOC and selected VOCs emitted from an office workstation furniture system

It should be noted that the test office workstation also exhibited "sink effect". Sink effect refers to the process by which some materials and furnishings adsorb VOCs in the air and re-emit them at a later time. An example is the smell of cigarette smoke in hairs and clothing that remains long after leaving a public place where smoking is allowed. Sink effect increases the time required for VOCs to approach their stable levels. For the test workstation, the degree of sink effect was found to be directly proportional to the boiling point of the VOC. In other words, the sink effect for VOCs with relatively high boiling points, such as 1-octanol was greater than that for compounds with lower boiling points, such as dichlorobenzene and decane.

VOC levels in buildings

Air samples were taken in 24 Canadian workplaces and 25 Canadian houses and analyzed for their VOC content (Tsuchiya and Kanabus-kaminska, 1990). Of the total of 66 VOCs detected, 34 were found in the workplaces and 56 were detected in homes. The VOCs that were detected at least four times, and in both workplaces and homes, are listed in Table 2.

Table 2. VOCs in Canadian Workplaces and Houses (mg/m^3)

VOC	24 Offices	(mean)	25 Houses	(mean)
Benzene	0.001-0.021	(0.008)	0.002-0.064	(0.017)
Toluene	0.002-0.072	(0.028)	0.003-0.159	(0.049)
Xylene	0.003-0.071	(0.020)	0.002-0.167	(0.033)
C_3benzene	0.003-0.095	(0.027)	0.003-0.054	(0.016)
CCl_3CH_3	0.004-0.071	(0.034)	0.003-0.063	(0.029)
C_2Cl_4	0.001-0.026	(0.011)	0.009-0.070	(0.032)
Dichlorobenzene	0.001-0.085	(0.020)	0.012-0.327	(0.115)
Ethanol	0.019-0.387	(0.119)	0.022-0.561	(0.183)
isoPropanol	0.05-0.13	(0.102)	0.014-0.897	(0.274)
Propanone	0.001-0.447	(0.074)	0.005-0.196	(0.069)
TVOC	0.1-13.3	(2.5)	0.1- 8.6	(1.8)
TVOC without copier		(1.2)		

Part II – Actions Determining the Indoor Environment

This part of the report provides building owners, managers, and engineers with the technical information and skills that are required to manage their buildings. Issues such as preparation of specifications for low-emitting building materials/products, identification of potential IAQ problems, and evidence supporting the best building operation practices for achieving acceptable indoor air quality are discussed.

Proactive Plans for Minimizing VOC Effects

The best solution to minimize VOC effects in office buildings is to develop a proactive plan that focuses on eliminating VOC sources rather than treating the symptoms. Two measures that have been successfully used to reduce VOC concentrations in the indoor air are the use of low-emitting materials/products and the venting of airborne contaminants associated with renovation and installation activities directly outside.

Low-emitting building materials/products

The best way to identify low-emitting materials/products is to ask all potential suppliers to submit their material/product samples to the same laboratory for testing. Given that hundreds of materials are used in buildings, testing all potential material samples may not always be practical. A more practical way is to ask potential suppliers to submit emission test reports or similar information. It appears that in anticipating such demands, several manufacturers' associations have developed protocols for helping their members to evaluate their products. The Business and Industry Furniture Manufacturers Association (BIFMA), for example, has developed a protocol for testing office furniture (BIFMA, 2000). The Carpet and Rug Institute (CRI) has developed a carpet labelling program for its members. Table 3 shows the maximum emission factors of total VOCs (TVOC) and selected VOCs under the Canadian carpet labelling program (CCI, 1993).

Table 3. Maximum Emission Factors under CCI/CRI Carpet Labelling Program

Chemical	Emissions ($mg/m^2/h$)
4-Phenylcyclohexene (4-PC)	0.1
Formaldehyde	0.05
Styrene	0.4
TVOC	0.6

Large organizations may consider developing a material emission database for internal use, by contracting laboratories to conduct emission testing on frequently used materials and products. In addition, the technical personnel can use software such as MEDB-IAQ (Zhang et al., 1999) to predict the effects of these materials and products on the IAQ level of a reference building to determine the maximum allowable emission rates of new materials and products or to explore trade-offs between material selection and ventilation strategy.

As an interim measure, Table 4 provides some default TVOC values that may be used for specifying low-emitting materials (Tucker 1990, Zhang et al. 1997).

Table 4. Default TVOC Values for Specifying Low-Emission Materials

Material/Product	USEPA Max EF ($mg/m^2/h$)[1]	Material/Product	IRC/NRC EF @ 30 d ($mg/m^2/h$)[1,2] Min	IRC/NRC EF @ 30 d ($mg/m^2/h$)[1,2] Max
Flooring	0.6	Vinyl flooring	0.05	1.71
		Underpad	0.02	0.19
		Carpet	0.01	0.46
Floor coatings	0.6	Wood stain	0.01	0.54
		Polyurethane coating	1.01	12.06
		Floor wax	0.17	0.99
		Paint/Primer	0.32	6.39
Wall covering	0.4			
Partitions	0.4			
Office Furniture	2.5 mg/h per WS			
Office Machines	0.25 $mg/m^3/h$			
Workstation			0.5 mg/h	
Others		Particleboard	0.50	1.87
		Plywood	0.12	0.29
		Oriented strand board	0.18	3.72
		Solid wood	0.06	2.15
		Gypsum board	0.02	0.23
		Acoustic tile	0.018	0.023
		Adhesive	0.0	109.7
		Caulking sealant	18.7	928.2

[1] The unit is $mg/m^2/h$ unless otherwise specified.

[2] The emission factors at 30 days were estimated using a power-law model determined data. The values are the minimum and maximum emission factors among those determined from three products in each category.

Minimizing material emission effects during installation/renovation

Installation and renovation activities lead to a significant increase in the VOC levels indoors. Because this increase is temporary, special measures can be used to minimize the effect. Figure 2 shows the TVOC profile immediately following recarpeting in an office.
The results indicate that the TVOC level is the highest immediately following the installation of the new carpeting, then decreases sharply with time, approaching a stable value after 10 days.

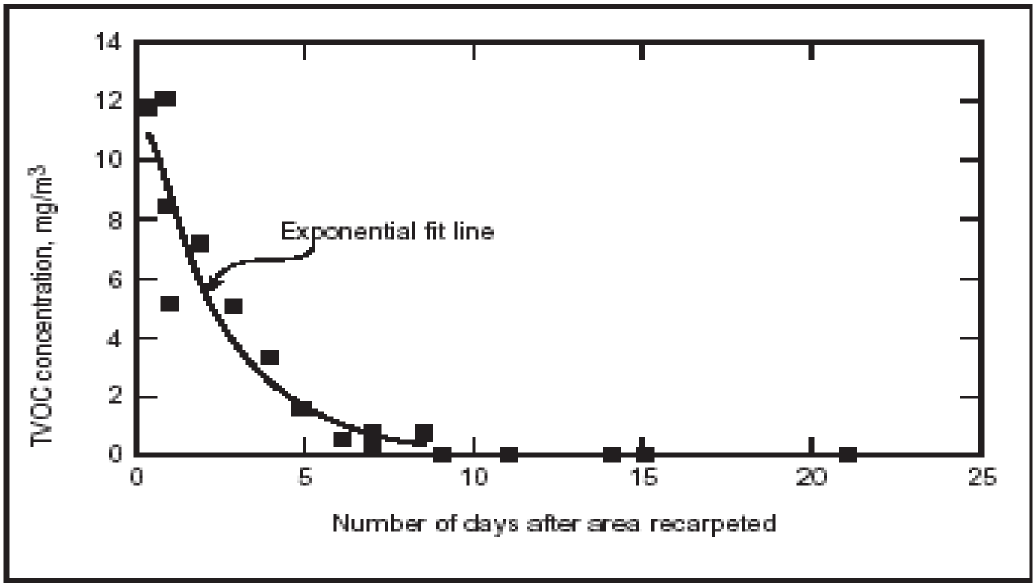

Figure 2. TVOC profile immediately after recarpeting an office
(This graph was supplied Dr. Gemma Kerr, InAir Environmental Ltd.)

Figure 3 shows the TVOC profile during and after a major renovation of a conference room in an office-laboratory building (Zhu et al. 1999). Similar to the results of Figure 2, the TVOC concentration shown in Figure 3 is the highest immediately following renovation. It then decreases sharply with time, becoming relatively stable at around 1 mg/m^3 after about one week. It decreases continuously at a much slower rate to a value of 0.14 mg/m^3 after 14 weeks.

The results shown in these two figures collectively illustrate the benefit of removing the increased amount of VOCs generated from renovation activities. Makeshift exhaust systems such as open windows, portable exhaust fans, and smoke shafts, should be used to vent VOCs directly to outside during renovation (time of highest VOC concentrations). Immediately following the renovation, for a period of one to two weeks, the VOC concentration is expected to be moderately greater than the level normally experienced in the building. The building's HVAC system, operated with an increased ventilation rate, should be capable of handling the extra VOC load.

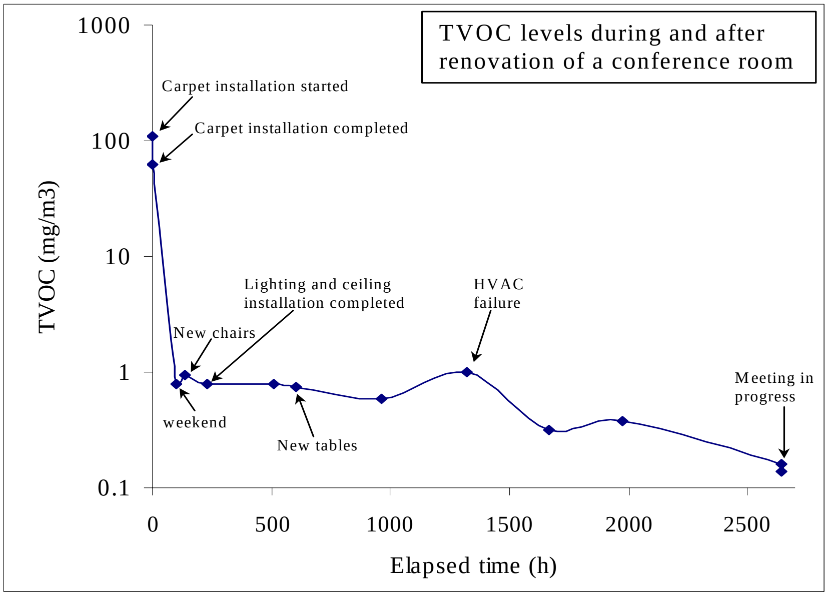

Figure 3. TVOC profile during and after a major renovation of a conference room

Diagnostic techniques for identifying potential IAQ and ventilation problems

Visual inspection

The most effective way to maintain an acceptable indoor air quality in buildings is to adopt a preventive approach by regularly conducting a visual inspection, also known as a walk-through inspection, together with an assessment of the operation of the building's HVAC systems. A walk-through inspection allows potential environmental problems to be identified and corrective actions to be taken before significant problems develop. A step-by-step procedure for conducting such an inspection is given in the first of the three PWGSC/NRC Manuals entitled, "Managing Indoor Air Quality – A Manual for Property Managers" (PWGSC/NRC, 1990). The inspection team usually includes the property manager, building operator, health and safety officer, consultant, and other interested parties.

Detailed measurement

Unfortunately, not all potential problems can be identified by a walk-through inspection: tests and measurements are required sometimes. The methods commonly required for conducting detailed measurements are given in the second PWGSC/NRC Manual entitled, "Controlling Indoor Air Quality - Ventilation Engineering Guide" (PWGSC/NRC, 1992).

It should be pointed out that not all test results will lead to concrete conclusions. The measurement of VOC levels in buildings is an example. A detailed VOC test involves taking air samples and analyzing them to identify the VOCs and determine their concentrations. However, there is a lack of established criteria for determining "acceptable" VOC concentrations in office and residential buildings.

Figure 4shows a meaningful way to use the VOC test that does not require the identification of "acceptable or unacceptable" VOC levels.

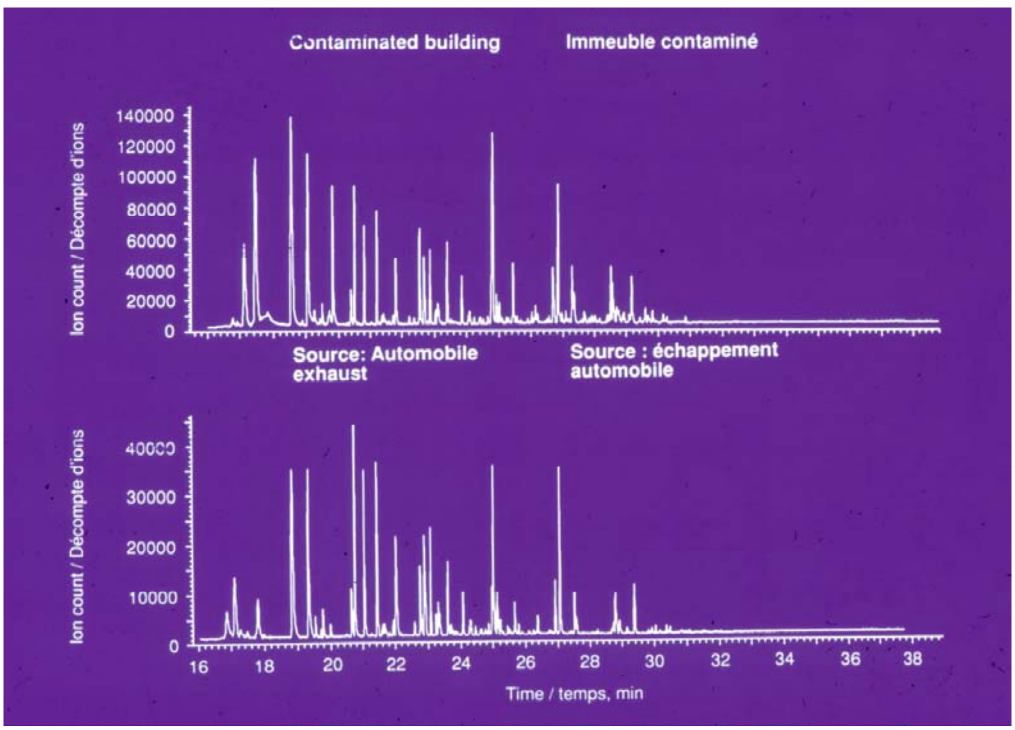

Figure 4. Gas chromatograms of a contaminated building and an automobile exhaust

There are two gas chromatograms shown in Figure 4. The upper one was obtained from a contaminated building. Since it was suspected that the main contamination source was the automobile exhaust from an adjacent parking lot, the gas chromatogram of the exhaust gas of an automobile is shown on the same figure. The close resemblance of these two gas chromatograms clearly confirms that some of the automobile exhaust did enter into the building through a nearby air intake. Because this method does not require a quantitative analysis of VOCs it is suitable for use by non-technical people.

The search for a simple pass and fail criterion for assessing indoor air quality has prompted the use of TVOC levels as an IAQ index. Using TVOC levels is advantageous because they are relatively easy to measure and practical to use. Unfortunately, the advantages do not outweigh the major disadvantage that there is little scientific basis for using TVOC as an IAQ indicator. The TVOC level does not recognize that VOCs have different toxicities. However, until a better index can be found, TVOC may be used as an indicator for possible IAQ problems. Additional information (CO_2 levels, concentrations of individual VOCs, walk-through inspection results, details of occupants' complaints) is needed to draw the correct conclusions in attempting to diagnose suspected IAQ problems.

Balancing between acceptable IAQ and energy use

The most commonly used strategy for controlling VOCs / IAQ in buildings is ventilation (dilution). To maintain an acceptable IAQ, a large amount of ventilation air is required. On the other hand, to conserve energy, the ventilation rate should be as low as possible. Therefore, to satisfy both, air cleaning and source control must be used together with ventilation to maintain acceptable IAQ.

Air cleaning

Air cleaning is the use of filtration techniques to remove contaminants from both the ventilation (outdoor) air and the indoor air. These techniques are essential for buildings located in urban centres or near industrial plants where the quality of the outdoor air may be worse than that of the indoor air. In office buildings, air filters are installed in almost all HVAC systems to remove dust and other particulate contaminants. A brief review of the commonly used air filters is given below (Miller, 2002).

High Efficiency Particulate Air filters (HEPA filters) are installed in HVAC systems for office buildings, laboratory buildings, hospitals, and clean rooms. HEPA filters are 99.97% efficient in capturing 0.3 micron particles. The sizes of most known bacteria range from 0.2 to 0.3 microns, and those of viruses range from 0.01 to 0.3 microns. Because viruses need a host in which to live, they are usually attached to bacteria or an object.

High efficiency air filters have a similar construction to HEPA filters. The efficiency ranges from 60% to 95% for bacteria and water droplets carrying viruses with sizes varying from 0.2 to 0.5 microns. For particles 1 micron or larger (e.g., anthrax), the efficiency increases to 99% or higher.

Activated carbon filters are used to remove odours and gaseous contaminants. This type of filter is not effective at adsorbing VOCs in the ppb (parts per billion) concentration range which are normally found in indoor air.

Electrostatic air cleaners with UV emitters are currently used in buildings, laboratories, and restaurants for removing contaminants and cigarette smoke. Their capture efficiency is 95% at 1 micron and decreases to 33% at 0.3 micron.

Source control

The primary function of source control is to prevent contaminants from getting into the indoor air. This can be achieved by minimizing the use of building materials and products with high emissions and by venting VOCs from identified sources directly outside, if practical. This method is the most economical and effective strategy for controlling VOCs/IAQ in buildings. Its usefulness, however, is yet to be recognized widely by building owners and managers as evidenced by the oft-used statement "the solution to pollution is dilution." Figures 5 and 6 illustrate the benefit of source control.

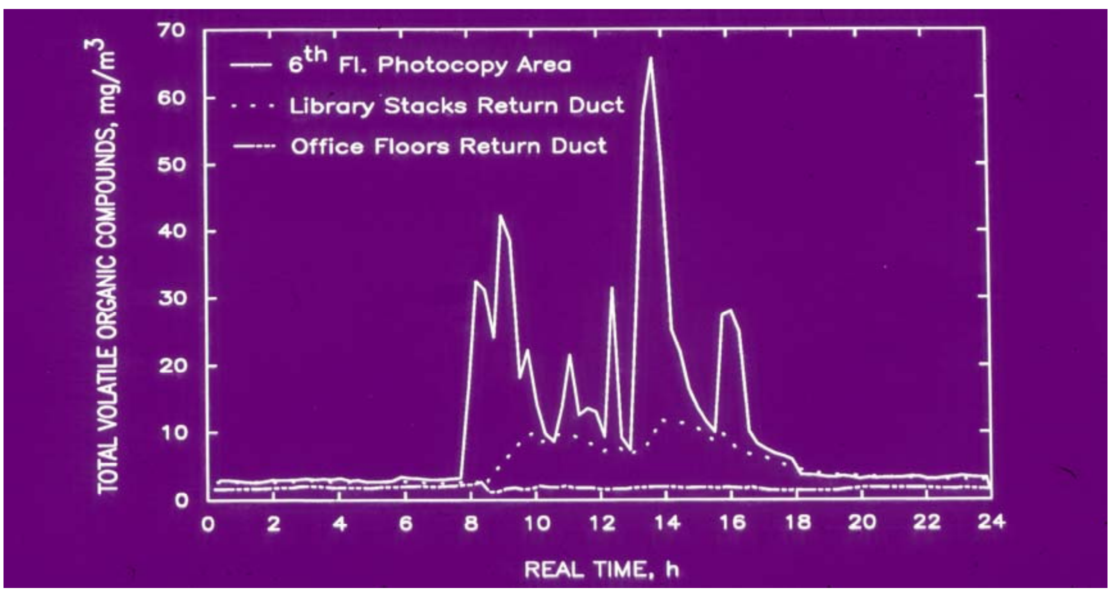

Figure 5. TVOC profile for a typical working day in a photocopying unit of a library

Figure 5 shows the measured TVOC profile of a typical workday in a problem work area where a number of photocopiers were located. The results showed that two large peaks, indicating high concentrations of VOC's, occurred at 9 a.m. and at 2 p.m. These periods corresponded closely with the periods when most of the photocopying was being done.

To determine whether ventilation alone could eliminate this pollution problem, the ventilation rate in the building was increased six-fold in stages from 0.5 to 3 air changes per hour and the TVOC concentrations were monitored for each air change rate. Figure 6 shows the relationship observed between TVOC concentration and air change rate. The results indicated that as ventilation rate increased from 0.5 to 1 air change per hour, the TVOC level decreased by about 30 ppm from 90 ppm to 60 ppm. A further increase in ventilation rate from 1 to 3 air changes per hour reduced the TVOC concentration to 45 ppm.

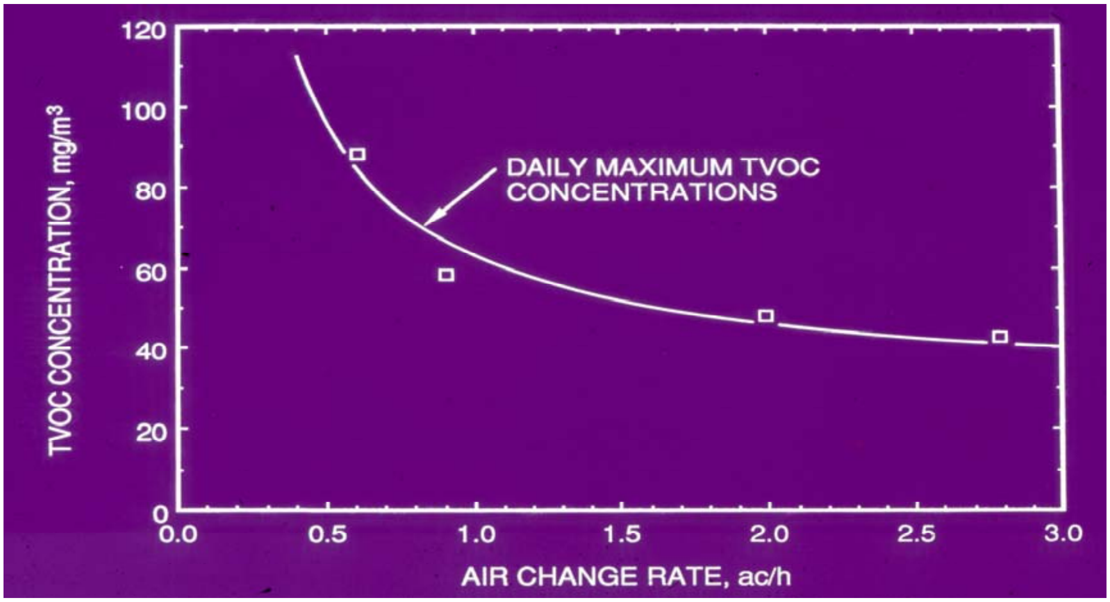

Figure 6. Daily maximum TVOC concentration vs. air change rate

The results suggest that the initial increase in the air change rate (from 0.5 to 1 ac/h) was very effective in reducing the TVOC concentration. Further increases in the air change were not nearly as effective. The results suggest that ventilation alone may not be able to lower the contamination level to a pre-set value when a prominent source of contaminants is present. In the case of an identifiable contaminant source such as a photocopier, a combination of source control, i.e., venting the exhaust of the photocopier directly to outside, plus ventilation to dilute generally dispersed contaminants is usually an effective approach to manage of the IAQ.

Ventilation.

The most frequently used strategy, and in most cases the only one available to building operators, is ventilation. Ventilation costs money because the outdoor air drawn into the building needs to be heated in winter and cooled in summer. To conserve energy, care must be taken to maximize the efficiency of the ventilation system. In this regard, a number of factors come into play. The factors affecting ventilation and energy use include air leakage and adequate ventilation.

Air leakage - air leakage is the infiltration of air through the building envelope. This uncontrolled flow of air through accidental openings in the building envelope can interfere with the intended function of the HVAC systems. Leaky buildings are more costly to heat and more difficult to ventilate properly than relatively airtight buildings. Figures 7 and 8 illustrate the effect of air leakage on ventilation air distribution and energy use.

Figure 7 shows a typical floor plan of a five-storey apartment building, indicating the locations of individual apartments. For this building, ventilation air is supplied to the corridor, and intermittently operated exhaust fans are located in each apartment. The design intention is to pressurize the corridor so that the ventilation air supplied to the corridor will flow into each apartment unit, preventing airflows from apartments into the corridor.

The tracer gas decay method was used to determine how well the design works. The method involves the injection of a small amount of tracer gas into the supply system and periodic measurements of the tracer gas concentrations at six locations on each floor. The detection of tracer gas at a measuring location means that the ventilation air has reached that location. The movement of the ventilation air could be best illustrated by comparing the measured tracer gas concentrations at two locations: Apts._02 and _08, one on each side of the corridor.

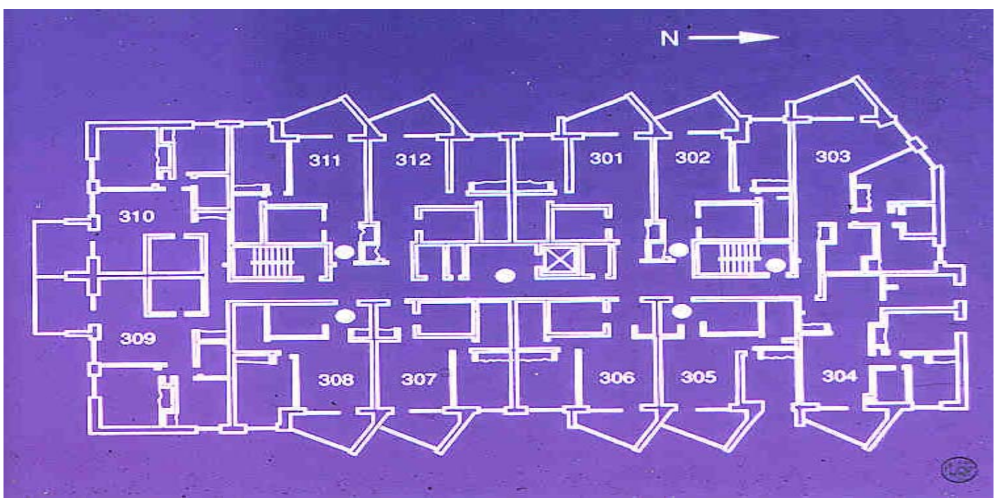

Figure 7. Floor plan of a typical floor in a five-storey apartment building

Figure 8 shows that immediately after the injection of tracer gas, the tracer gas was detected at Apt.208 but not at Apt.202. This suggests that the units on one side of the corridor were over-ventilated (because they also received the ventilation air for the units across the corridor) and that those on the other side were either under-ventilated or relied on air leakage for ventilation. As a result, additional energy was needed to heat that air. For proper ventilation, it is necessary to minimize air leakage.

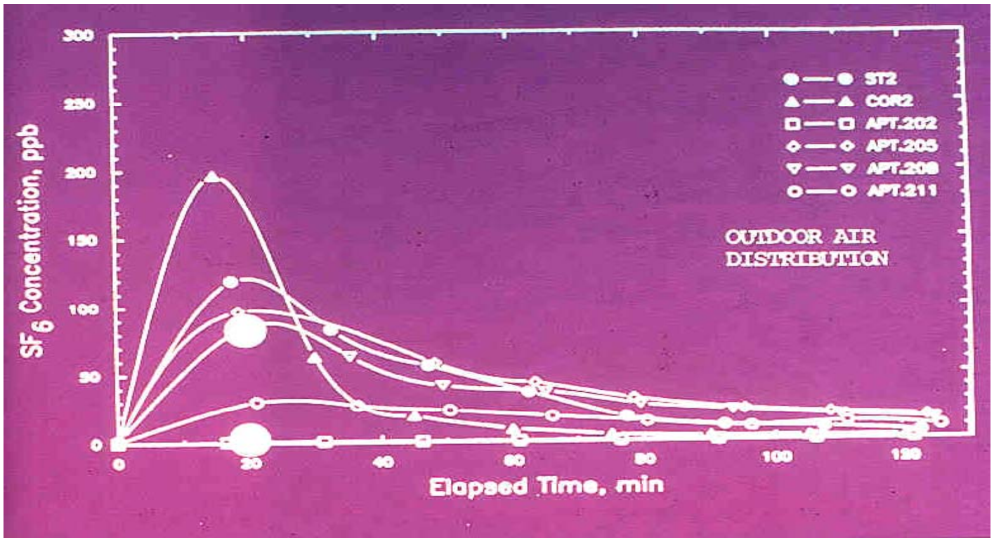

Figure 8. Ventilation air distribution on a typical floor

<u>Adequate ventilation</u> - adequate ventilation, from the engineering point view, should satisfy three conditions: acceptable outdoor air supply, adequate ventilation rate, and proper air distribution.

Acceptable outdoor air supply means that the outdoor air supply should not be contaminated by nearby pollution sources, such as parking lots, cooling towers, large green space where fertilizer and pesticides are frequently used, etc. For HVAC engineers, this means that air intakes should be located as high in the building as practical and as far from adjacent contaminated sources as possible. Adequate ventilation rate is achieved when the ASHRAE recommendations are met (ASHRAE Standard 62, Ventilation for Acceptable Indoor Air Quality, 1999). For office buildings, the ventilation rate should be 10 L/s per person or 20 cfm per person. Proper air distribution requires ventilation air to be delivered to the occupants, i.e., throughout the occupied space.

<u>CO_2 demand-controlled ventilation</u> - A CO_2 demand-controlled ventilation system can help balance indoor air quality with energy consumption by regulating the ventilation air rate based on the number of occupants in the building or in a particular space in the building. The feasibility of using such a system to control the ventilation rate in office building is briefly discussed below.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommends ventilation rates for buildings based on the maximum (design) number of occupants. For buildings such as office complexes and schools, where the number of occupants varies significantly over time (i.e., the building is typically occupied only during the day), it may be possible to control ventilation rates based on the number of occupants at a given time. One approach for office buildings is the demand-controlled ventilation system, which uses occupant-generated CO_2 as the control index. The ventilation controllers used in such systems are similar to thermostats used to control the furnaces in homes. Thermostats are located in places where the temperature represents roughly the average temperature of the whole house. As the temperature at the thermostat location rises and falls, the thermostat sends a signal to turn the furnace on and off. A CO_2–based demand-controller senses the CO_2 concentration at a representative location in a building and sends a signal to turn on or turn off the ventilation fans accordingly.

Studies in office buildings have shown that the concentration of CO_2 increases and decreases with the number of occupants. Therefore, it is possible to control ventilation rates based on measured CO_2 concentrations.

In order for occupant-generated CO_2 concentrations to be used to control the ventilation rate, a building, or a space, should meet the following three conditions:

- The CO_2 concentration must be proportional to the actual number of occupants.
- The CO_2 concentration must be approximately the same on all floors, or throughout the space, and there must be suitable locations for placing the CO_2 sensors, (where the concentrations of CO_2 are representative of those throughout the building, or the space, i.e., the interior air should be well-mixed).
- There must a relationship between the CO_2 concentration and the air change rate.

Using these conditions as criteria, IRC conducted a study in a 22-storey office tower with an interior volume of approximately 113,700 m^3. The building has seven all-air constant-volume supply-air systems and two return-air systems. Four of the supply systems provide air to the interior zones of the east and west floors in the upper and lower half of the building. The remaining three supply systems provide air to the southern perimeter, the east and eastern half of the northern perimeter, and the west and western half of the northern perimeter, for the entire height of the building.

The results shown in Figure 9 confirm that the CO_2 concentration varies according to the number of occupants and the first condition is met. The CO_2 concentration is low during the night. It begins to rise as the employees arrive in the morning and peaks around noon. It drops somewhat during the lunch hour, then picks up as the employees return to work and peaks again around 4 p.m. Once the occupants begin to leave, the concentration drops continuously until it reaches the nightly level.

On all test floors, the CO_2 concentrations measured at various locations in the occupied spaces agreed closely with the concentration measured at the return-air shaft of that floor, suggesting that the latter measurement provides a good indication of the CO_2

concentration for the entire floor. Similarly, the CO_2 concentrations measured at the return-air intakes of individual floors agreed closely with the measurements at the tops of the two main return-air shafts. The finding suggests that the tops of return-air shafts are suitable locations for CO_2 sensors. The second condition is met.

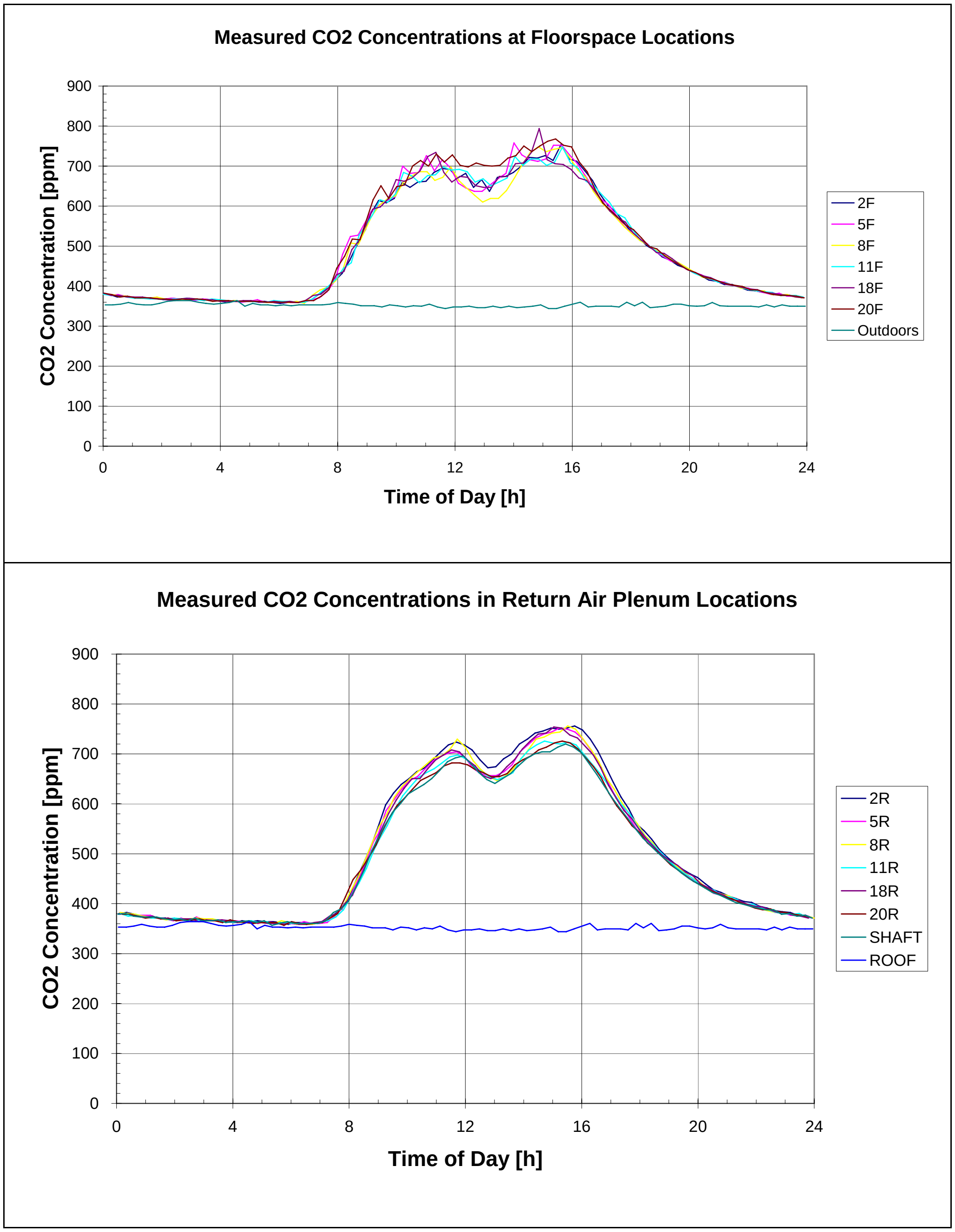

Figure 9. CO_2 profiles in the floor space and return duct of different floors

The final step in the above study was to establish the relationship between the measured CO_2 concentrations and the air change rate. Figure 10 shows the daily maximum and the daily average CO_2 concentrations at the various air change rates (ventilation rates). The results suggest that a good correlation exists between the measured CO_2 concentrations and the air change rates. Thus, a CO_2-based demanded-controlled system can be used to control the building's ventilation rate and provide potential energy savings by helping to avoid periods of excess ventilation.

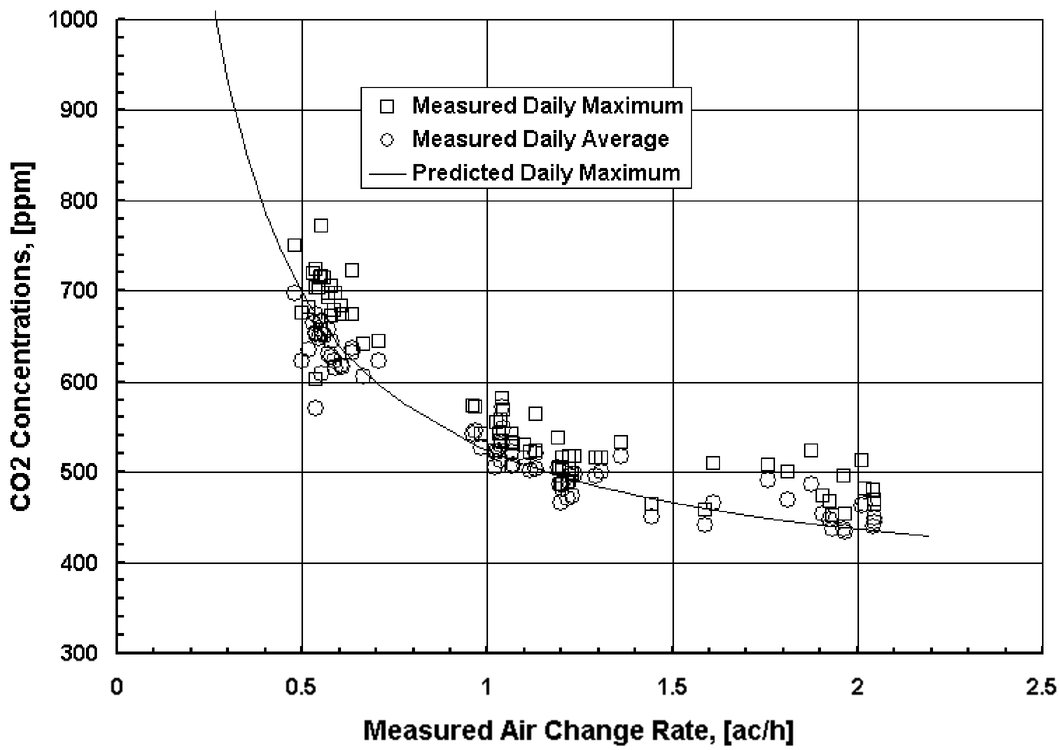

Figure 10. Relationship between daily maximum (or average) CO_2 concentration and air change rate

Part III – Best Practice for Managing IAQ-VOCs in Office buildings

Select low-emission building materials and products

- Ask potential suppliers and /or manufacturers to supply:
  - emission test reports (VOC emission rates, testing laboratory, and test methods and conditions);
  - data useful for assessing potential emissions;
  - simulation results demonstrating the impact on the IAQ of existing buildings.
- Develop a database for internal use by:
  - conducting emission testing on materials and products from potential suppliers and manufacturers;
  - using the MEDB-IAQ software tool to predict the effects on the IAQ .

In the absence of measured data, use the values (USEPA and IRC/NRC) in Table 5 as default emission factors for simulation calculations to estimate the IAQ consequences of various material and product choices. The emissions of each source are considered constant in this case.

Table 5. Emission factors (EF in mg/m^2/h) for TVOC

Material/Product		USEPA	IRC/NRC [2]			
			EF @ 24 h [1]		EF @ 96 h [1]	
		Max EF [1]	Min	Max	Min	Max
Flooring	Particleboard	0.6	3.87	6.90	2.12	4.35
	Plywood		0.22	0.67	0.19	0.46
	Oriented strand board		0.27	0.98		1.76
	Solid wood		0.07	4.53	0.05	3.55
	Vinyl flooring		0.05	3.77	0.07	2.73
	Underpad		0.10	0.45		0.28
	Carpet		0.20	1.91	0.07	0.99
Floor coatings	Wood stain	0.6	18.2	124.4		52.3
	Polyurethane coating		88.1	154.5	3.88	359.3
	Floor wax		51.4	409.0	5.55	26.0
	Paint/Primer		29.9	216.2	0.34	19.0
Wall/ceiling covering	Gypsum board	0.4	0.07	4.50	0.05	3.55
	Acoustic tile		0.06	0.17	0.04	0.23
Partitions		0.4				
Office Furniture		2.5 mg/h per WS				
Office Machines		0.25 mg/m^3/h				
Workstation			0.5 mg/h			
Others	Adhesive		3.28	659.1	3.88	359.3
	Caulking sealant		448.0	10467.2	51.13	3842.6

[1] The units are mg/m^2/h unless otherwise specified.

[2] The values are the minimum and maximum emission factors among those determined from testing three products in each category.

Minimize material emission effects during installation and renovation activities

- During installation and renovation:
  - isolate the affected area from the rest of the building;
  - seal off return air grilles in the affected area and keep supply air system operating;
  - vent the affected area through leeward side windows (summer only), a smoke shaft, or stair shafts with outside doors at roof top;
  - use portable exhaust fans to assist this venting.
- Immediately after completion:
  - operate HVAC systems with a ventilation rate of up to 20 L/s/person (40 cfm), or greater depending on the system capacity and outdoor air temperature (watching closely for warnings of coil freezing);
  - after two to four weeks, depending on outdoor air temperature, return the HVAC system operation to the normal ventilation rate.

Balance IAQ with energy use through effective use of ventilation

- Avoid contaminated ventilation air by:
  - locating air intakes as high as possible in the building;
  - locating air intakes as far away as possible from pollution sources such as cooling towers, exhaust system discharges, chimneys and stacks, loading dock entrances, parking lots, street traffic, and plumbing stacks;
  - install drains, louvers, wire-mesh screens inside air intakes to prevent rain, debris, insects and small animals from entering the HVAC system.
- Supply air to the occupied zone and avoid short-circuiting supply air to return grilles.
- Improve building envelope airtightness.
- Provide dedicated exhaust for localized emission sources.
- Take advantage of free-cooling, when weather conditions permit.
- Control ventilation rates using occupant-generated CO_2, if feasible.
- Operate the ventilation system to depressurize the parking garage with respect to the rest of the building, and pressurize the parking attendant's booth with outdoor air.
- Pressurize stairwell and elevator lobbies serving the garage floors by:
  - using tight-fitting, self-closing doors,
  - sealing around ducts and pipes that extend through the garage to other areas,
  - installing CO sensors and alarm; link them to ventilation system controls.
- Pressurize the areas adjacent to the loading dock with a separate supply air system by:
  - installing easily closed access doors with self-closing devices (leading to adjacent areas);
  - using automatic vehicle entrance and exit doors or air curtains to minimize wind-induced air infiltration.

Establish an effective preventive maintenance program

- Develop a preventive maintenance manual including:
  - preventive maintenance procedures and schedules for implementation;
  - calibration instructions and schedule for various sensors;
  - HVAC fault-identification and fault-location procedures;
  - equipment information such as warranty coverage and manufacturers' help hotline contact coordinates.
- Ensure that building operators are familiar with indoor environment standards, potential contaminant sources, and the building's HVAC control system.
- Maintain a thorough log of all maintenance activities.
- Perform annual checks on HVAC system operation by ensuring that all components are functioning, properly adjusted and maintained. Pay particular attention to fans, air filters, humidifiers, and dampers.
- Service controls by testing, calibrating, and adjusting sensors at least annually. These controls include:
  - CO sensors in parking garages and other locations;
  - thermostats, humidity sensors, and pressure sensors;
  - CO_2 sensors;
  - time clocks, and
  - dampers and valves, and their actuators.
- Check and replace air filters:
  - as recommended by the manufacturer;
  - as indicated by pressure sensors; or
  - when wet or damaged to prevent microbial growth.
- Ensure that air filters are functioning properly by ensuring that they fit their frames properly.
- Perform regular cleaning of system components to minimize dusts, bacteria and mould that may get into the supply air. (Use appropriate personal protective equipment). Components to be regularly cleaned include:
  - electrostatic precipitators;
  - humidifiers;
  - fan coil units, radiators and induction units;
  - cooling towers;
  - air intakes, and air ducts; and
  - refrigerant coils.
- Perform regular maintenance. Pay attention to mechanical rooms, fan rooms, and standing water (Use appropriate personal protective equipment). Also:
  - replace damaged ceiling tiles promptly if the above-ceiling space is used as a supply or return air plenum;
  - store chemicals and cleaning products properly to avoid contamination of the ventilation air;
  - follow closely manufacturers' instructions when cleaning fluids are used;
  - clean up water spills as soon as possible to prevent mould growth.

Act proactively to manage IAQ & VOCs

- Develop a proactive program for managing IAQ & VOCs by conducting an annual walk-through building inspection using, as a guide, the check list in the manual <u>Managing Indoor Air Quality</u> published by NRC/PWGSC. Correct any identified potential IAQ problems as soon as possible.
- Consider these additional tips for conducting a successful building inspection:
  - Offices with wood paneling may have intermittent IAQ problems due to chemical reactions between ozone (often produced by office machines and free-standing or desktop air-purifiers) and α-pinene (contained and emitted by the wood paneling). Exhaust office machines directly outside or increase ventilation to reduce ozone concentrations indoors.
  - Pay careful attention to inadequate airflow from supply air diffusers, the locations of air intakes, draughts, noise, glare on VDTs, odours, and wet surfaces.
  - If feasible, measure concentrations of CO_2 and TVOC. Consult technical personnel if the levels of CO_2 and TVOC are over 800 ppm and 2.5 mg/m^3, respectively. (Note: occupant complaints may occur at lower levels, i.e., 600 ppm, and 1 mg/m^3 for CO_2 and TVOC, respectively.)
- Maintain thorough logs of all occupants' complaints and remedial work.
- Avoid complex measurements without knowing how to interpret the results.
- Facilitate and encourage communication between building managers, operators, and occupants. It is essential to effective management of IAQ in the workplace.
- Avoid using phrases such as "identifying IAQ problems".
- Avoid asking occupants about their impression of the IAQ. This task should be conducted by professionals specially skilled in administering and interpreting occupant questionnaire surveys.
- Consider contracting a professional to conduct an occupant survey before performing expensive diagnostic tests.

Acknowledgement

This study is sponsored by members of the Consortium for Material Emissions and IAQ Modelling - Phase II (CMEIAQ-II), and Canadian Panel for Energy Research and Department (PERD), and National Research Council Canada. The authors wish to thank Ms Alison Danforth for reviewing this report.

References

ASHRAE, 1999. Ventilation for acceptable indoor air quality, ANSI/ASHRAE Standard 62-1999, ASHRAE.

BIFMA, 2000. American National Standard for panel-based workstations, Office furniture-test for formaldehyde and TVOC emissions for low-emitting panel-based workstations, BIFMA, International, 2000.

CCI, 1993. Indoor air quality carpet testing program, Canadian Carpet Institute, 1993.

Health Canada, 1989. Exposure guidelines for residential indoor air quality, Health Canada, 1989.

Jones, A.P., 1999. Indoor air quality and health, Atmospheric Environment 33, pp.4535-4564, 1999.

Miller, J.D., 2002. Defensive filtration, ASHRAE Journal, ASHRAE, pp.18-28, December 2002.

MRC IEH, 1999. Volatile organic compounds)including formaldehyde) in the home, MRC Institute for Environment and Health, University of Leicester, UK, 1999, www.le.ac.uk/ieh.

PWGSC/NRC, 1990, Managing indoor air quality - a manual for property managers, IRC, NRC, 1990.

PWGSC/NRC, 1992. Controlling indoor air quality - ventilation engineering guide, IRC, NRC, 1992.

Tsuchiya, Y. and Kanabus-kaminska, J.M., 1990. Pilot study on indoor air quality, presented at the NATO/CCMS (Committee on the Challenges of Modern Society), Ste. Adele, Quebec, August 1990, IRC-P-3001.

Tucker, W.G., 1990. Building with low-emitting materials and products: where we are stand?, Proceedings, The fifth International Conference on Indoor Air Quality and Climate, Indoor Air'90, Vol.3, pp.251-256, Toronto, Canada.
WHO, 1983. Indoor air pollutants: exposure and health effects, EURO Reports and Studies No.78, World Health Organization, Copenhagen.

Woods, J. E., 1989. Cost avoidance and productivity in owning and operating buildings, Problem buildings: building-associated illness and the sick building syndrome (Cone, J.E. and Hodgson, M.J., eds), Occup Med State of Art Rev, 1989, Vol. 4, pp. 575-92.

Yu, C. and Crump, D., 1998. A review of the emission of VOCs from polymeric materials used in buildings, Building and Environment, V. 33, No. 6, pp.357-374.

Zhang, J.S., Kanabus-Kaminska, M, Shaw,C.Y., Lusztyk, E., Magee, R.J., Brouzes, M.A., Nong, G, and Wang, J.W., 1997. Characterizing the emissions of volatile organic compounds from a workstation system, Healthy Buildings/IAQ 97- Global issues and regional solutions, Washington, D.C., vol. 3, pp. 521-526.

Zhang, J.S., Zhu, J.P., Magee, R.J., Lusztyk, E., Yan, A., and Shaw, C.Y., A database of VOC emissions from building materials, Proceedings, the first NSF International Conference on Indoor Air Health, pp. 87-96, May 3-5, 1999, Denver, USA.

Zhu, J.P., Zhang, J.S., Magee, R.J., and Shaw, C.Y., 1999., Measurement and modelling of indoor VOC levels during and after room renovation - a case study, Proceedings, the 8th International Conference on Indoor Air Quality and Climate, Indoor Air'99, Vol. 5, pp.235-240, Edinburgh, Scotland, 1999.