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Maintaining Indoor Air Quality

Through the Use of HVAC Systems

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General Enquiries:
Institute for Research in Construction
National Research Council of Canada
Ottawa, K1A 0R6
Telephone: (613) 993-2607
Facsimile: (613) 952-7673

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Frank Vaculik, M. Eng.
Acting Manager
Productive Work Environment Division
Architectural and Engineering Services
Public Works and Government Services Canada

C.Y. Shaw, Ph.D.
Senior Researcher
Institute for Research in Construction
National Research Council of Canada

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Introduction

The primary readership targetted with this publication is building owners and property managers, and building operators. The information contained herein will give them an understanding of the concepts basic to achieving indoor air quality (IAQ) that is acceptable to the occupants of their buildings. Such an understanding enables building owners and property managers to fully appreciate the ideas and recommendations that HVAC engineers offer them with regard to providing effective ventilation. This manual also provides building operators with practical guidelines for the efficient and effective operation of HVAC systems so that they can maintain acceptable indoor air quality in their buildings.

Ventilation is effective when it can remove air high in indoor-generated contaminants and replace it with outside air. To achieve this cost-effectively many factors need to be considered since the conditions within and outside a building are always changing: within, there can be changes in use which, in turn, can change the population density of an area and, therefore, the amount of outdoor air required. Outside, the seasons change. On weekends or at night, when few people are working, few contaminants are generated.

All these changes in conditions affect indoor air quality. Therefore, the ventilation system has to be operated so that it adapts to these various changes in a cost-effective manner.

There are numerous contaminant sources in buildings, for example, those produced by human occupants and by operating office equipment, and those that are constantly given off by materials in the building. Contaminants emitted constantly are the ones that require flushing out following a weekend when the ventilation system has been turned off.

Knowing about air contaminants — where, when and how quickly they are generated — determines how the ventilation system should perform to provide the appropriate number of air changes for the occupants of a building. The measure of performance is always relative to standards. The standards for indoor air quality are prescribed by the Health and Safety Standard and by the Acceptable Indoor Air Quality Standard, each prepared by a different organization. In office buildings, the acceptable level of IAQ is defined as that which would provide an indoor environment conducive to the productivity of workers.

This publication is the third volume in a series of three manuals developed in conjunction with Public Works and Government Services Canada (PWGSC). The manuals were designed to help building owners, property managers and HVAC operators achieve acceptable indoor air quality in office buildings. The other volumes are called *Managing Indoor Air Quality: a Manual for Property Managers* and *Controlling Indoor Air Quality: Ventilation Engineering Guide* (see References).

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1 Purpose

The purpose of this document is to help

- building owners, property managers, and building operators to understand the operation of HVAC systems
- building engineers/operators to operate HVAC systems for maintaining acceptable indoor air quality
- designers and ventilation engineers to commission or re-commission HVAC systems.

All those mentioned above are likely to be involved in the implementation of a suitable ventilation strategy for achieving indoor air quality that is acceptable to the occupants of a building.

2 Scope

The document explains in detail the general ventilation process that is achievable with HVAC systems typically installed in office buildings and provides a guide on how to remove air contaminants from ventilated office spaces effectively, reliably, and energy-efficiently, both before and during occupancy.

The document does **not** include detailed explanations of:

- the use of HVAC systems for the control of off-gassing from freshly installed materials
- the use of exhaust systems for the control of local sources of air contaminants (see referenced literature)
- the application of HVAC systems for the achievement of IAQ that would be considered acceptable by people with environmental hypersensitivity.

3 Background

Industry and governments reacted to the oil crisis in the 1970s by introducing energy-conservation programs for buildings. While these led to tighter buildings, a new problem came to light: the "sick building" syndrome. In response to this new dilemma, the American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. (ASHRAE) accelerated the development of a knowledge base for ventilation processes. ASHRAE ventilation standards have changed twice since the oil crisis. First, to accommodate the pressures of the energy-conservation program and then to arrive at a standard for acceptable indoor air quality. The current version of the standard, *ASHRAE Standard 62-1989,* strikes a balance between the objectives of acceptable indoor air quality and energy conservation.

ASHRAE Standard 62-1989 is a standard for achieving indoor air quality acceptable to most occupants of buildings. It is based on scientific information, where such information exists, and beyond that on sound judgment.

4 Air Contaminants

From the perspective of a ventilation engineer, there are typically two types of spaces in an office building:

1. the spaces that are used for office functions, including workstations in open space, closed or private offices, and meeting rooms; and

2. supporting spaces such as washrooms, storage rooms, garages and commercial areas.

Within the space used for office functions, air contaminants are generated by base building materials, fit-up materials, office equipment, and people. In the supporting spaces, air contaminants stem from washrooms, cars in underground garages, materials in storage spaces and equipment on adjacent commercial floors. Also, an HVAC system itself can be a major contaminant source if it is not properly maintained.

Air contaminants from the outside such as those emitted by nearby chimneys and stacks, or by local traffic, can also enter an office building. These contaminants can be controlled by the proper location of outdoor-air intakes. This measure, however, is not necessarily effective in all weather conditions.

Air contaminants generated inside a building can be controlled by an appropriate ventilation process.

5 Ventilation Processes

Two ventilation processes are being considered here: the localized exhaust process and the general ventilation process.

The localized exhaust process is normally used in office buildings to control localized sources of air contaminants; for example: photocopiers, fax machines, food processing and serving areas, and washrooms. Although meeting rooms are also subject to localized sources of air contaminants, they are seldom included in the localized exhaust process. Their ventilation requirements call for special consideration (see Section 5.3).

The general ventilation process is used to control such sources of air contaminants as people occupying office workstations, fit-up materials, and base building materials from where the contaminants are distributed throughout the building, yet cannot be easily removed at the source.

Use of a localized ventilation process is more effective in eliminating contaminant build-up and should be implemented not only where required by code, but wherever the source of contaminants is localized. This measure reduces the burden on the general ventilation process for achieving indoor air quality acceptable to most occupants of a building.

5.1 Localized Exhaust Process

A localized exhaust process normally involves two interlocked systems: a make-up air system and an exhaust system.

Make-up air must always be provided to maintain the desired air pressure in the ventilated space. It can be provided either by a dedicated make-up air unit or by the HVAC system of a building.

Exhaust systems are used to capture air contaminants from their sources by drawing them into the exhaust-air duct and discharging them directly to the outdoors. The effectiveness of these systems can be very high and depends both on the distance of the source from the exhaust intake and on the air velocity at the exhaust intake. Exhaust systems for washrooms, janitors' rooms, and other special-purpose rooms containing sources of air contaminants are regulated by codes and are, therefore, normally installed as part of the base building system.

Tenant-installed exhaust systems, dedicated to localized air-contaminant sources, e.g. photocopiers, are highly recommended. They can prevent locally generated air contaminants from spreading throughout the office space. In buildings where such systems are not installed but are, in fact, needed, the locally generated air contaminants are likely to overtax the general ventilation process to a point where the HVAC system may no longer be able to maintain an acceptable indoor air quality throughout the building.

5.2 General Ventilation

General ventilation helps to lower the concentration of the contaminants through a combined process of mixing, dilution and removal of the air and is provided by the HVAC system of the building. The basic air-circulation system consists of a supply-air fan and a return-air fan. The supply-air fan delivers the supply air, which includes an adequate amount of outside air as required by *ASHRAE Standard 62-1989*, to the occupied spaces, where it mixes with the inside air. The return-air fan draws an amount of this mixed air back into the HVAC system, where some of it is discharged to the outdoors. The air remaining in the HVAC system is then mixed with the outdoor air and recirculated to the spaces.

5.2.1 Mechanism of Contaminant Reduction

For air contaminants generated by an internal source, the mixing and dilution take place first in the occupied space, near the sources of air contaminants. The air-contaminant mixture is then drawn back into the return duct where it mixes with the air-contaminant mixtures coming from other occupied spaces. A portion of this mixture is then exhausted directly to the outdoors. The remaining portion, which is recirculated back to the office space, is further diluted when it mixes with the continuous supply of outdoor air just downstream of the outdoor air intakes.

The process of mixing and dilution is relatively ineffective in removing air contaminants, especially when the rate of outdoor-air supply is set at the minimum during the heating and cooling seasons. In practice, the process can lower the concentration of contaminants only to a certain level.

Figure 1 shows a typical result of using the ventilation air to dilute the concentration of the total volatile organic compounds (TVOCs) generated by photocopying machines in the workstations of an office building. Tripling the amount of ventilation air from the building's normal ventilation rate of 0.9 to 2.8 air changes per hour (ac/h) resulted in a concentration reduction of only 24 percent, i.e. from 58 mg/m^3 to approximately 44 mg/m^3.

> Ventilation air is that portion of supply air that is outdoor air. ASHRAE Standard 6.2 also allows recirculated air that has been treated (filtered) to be used as ventilation air.

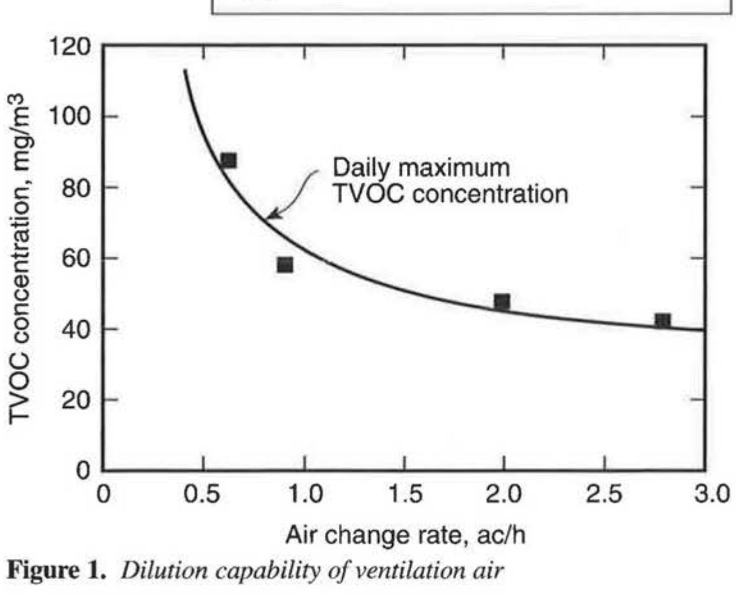

Figure 1. *Dilution capability of ventilation air*

The degree of reduction of the air-contaminant concentration depends on:

- the generation rate of the contaminants
- the volume of the space served by the HVAC system
- the ventilation rate or the number of outdoor-air changes in the ventilated space
- the concentration of the same contaminants outdoors.

5.2.2 Patterns of Contaminant Build-Up and Decay

A general ventilation process can produce one of three possible results, depending on the mode of operation and the activity or presence of contaminant sources: rapid increase of contaminants, asymptotic increase, or exponential decay.

Rapid increase (Case A). A rapid increase arises when the release of the contaminant has just started and the concentration of the contaminant increases linearly whether the HVAC system is on or off. This situation occurs typically in an office building when the office workers arrive for the day or when they start to operate such office equipment as photocopiers. It also occurs during unoccupied hours, when the HVAC system is turned off, because of off-gassing from building and fit-up materials. These materials continue to produce contaminants past their initial off-gassing phase at a constant, or nearly constant, rate.

Asymptotic increase (Case B). After the initial increase, described in Case A, the rate of increase declines substantially. The concentration of contaminants continues to increase until it approaches a steady-state concentration.

Exponential decay (Case C). With the HVAC system running and with few or no emissions from internal sources, the concentration of contaminants decays exponentially. This situation occurs shortly after occupancy hours, when people have turned off the sources of contaminants, i.e. office equipment, and left the building.

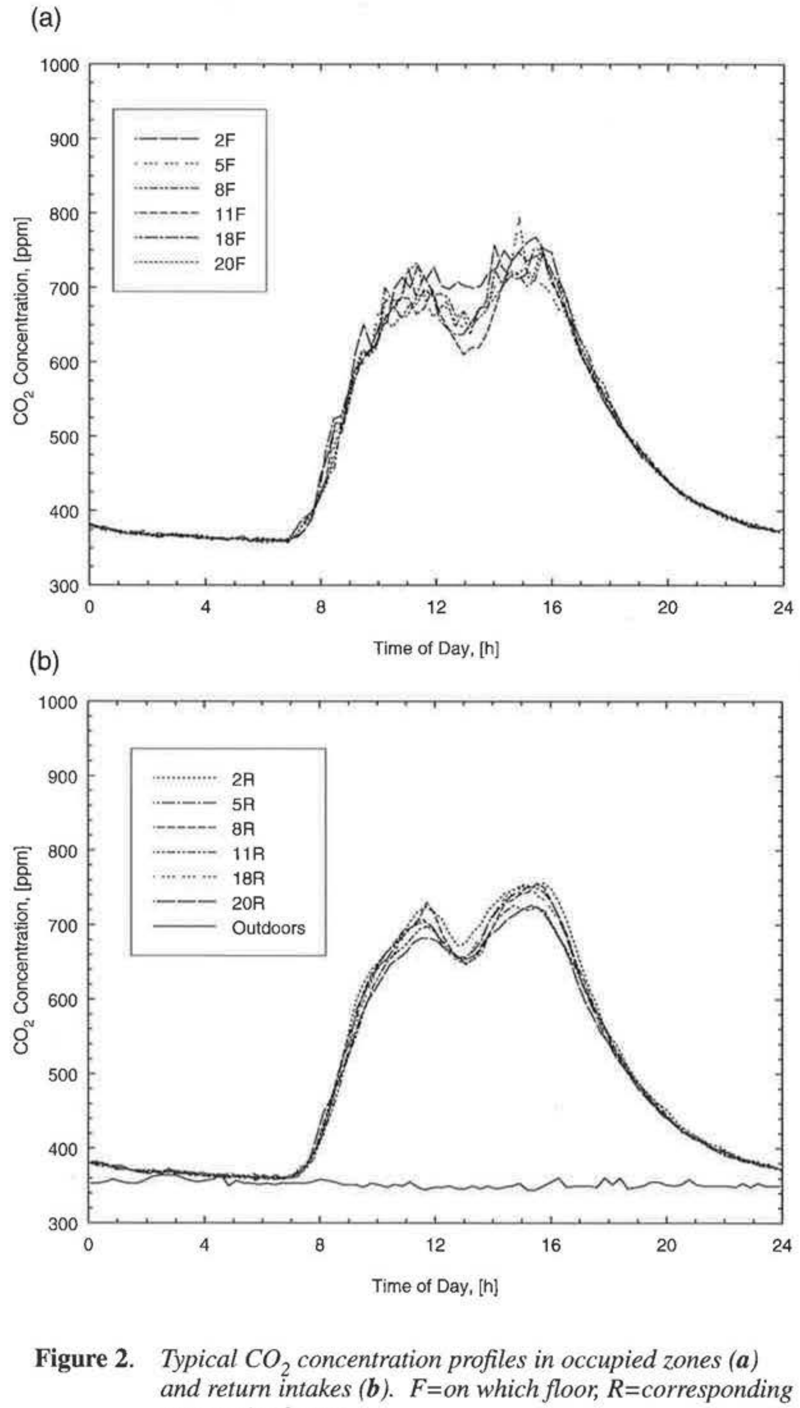

Figure 2. *Typical CO_2 concentration profiles in occupied zones (**a**) and return intakes (**b**). F=on which floor, R=corresponding return air plenum.*

5.2.3 Contaminant Concentration Profiles

When operating, an HVAC system controls all air contaminants simultaneously. The concentration profiles of the contaminants depend on the emission rates, the operating schedule of the HVAC system, and the amount of outdoor air used. In office buildings, some of the many sources may emit contaminants only during hours of occupancy, some intermittently, and some continuously.

Three frequently observed contaminant concentration profiles are described below. Each demonstrates various combinations of the three contaminant build-up and decay patterns discussed in Section 5.2.2.

Contaminants produced by occupants. Human occupants produce carbon dioxide (CO_2), water vapour, particulate, biological aerosols and other contaminants, at a relatively constant rate. The daily CO_2 concentration measured for the floor space of an office building may be used as an indicator of contamination build-up. Figure 2 shows typical daily CO_2 concentration profiles measured in the occupied zones and in the return air ducts of a 20-storey office building where a constant amount of outdoor air was supplied through the HVAC system. At about 7:30 a.m., indoor levels increased (Case A), reaching the first peak concentration at noon (Case B). The level subsequently decreased slightly during the lunch period and then increased again to reach the daily maximum concentration at about 2 p.m. The CO_2 concentration then decreased steadily after 4 p.m., reaching the outdoor level at about midnight (Case C).

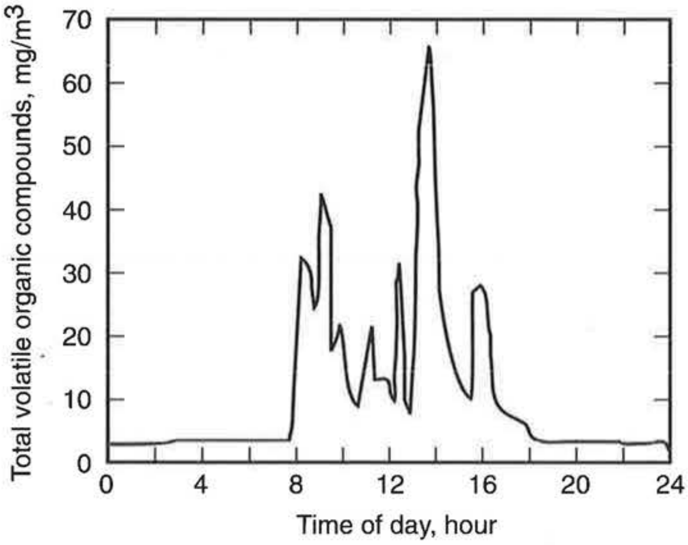

Figure 3. *TVOC profile produced by copying machines in an office space*

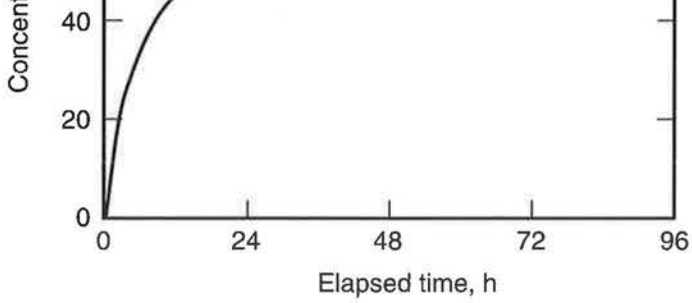

Figure 4. *Contaminant build-up in a closed room with HVAC system off*

Contaminants produced by operating office equipment. Office equipment produces contaminants when in operation. Figure 3 shows typical concentrations of TVOCs produced by photocopiers. The measurements were taken in an occupied zone surrounded by six photocopiers. The results for this zone reflect daily periods of peak photocopying activity at about 9 a.m. and 2 p.m. (Cases A and C). Levels of contaminants in this area rapidly decreased after the machines were turned off and after office hours (Case C). This profile may be used to represent the contaminant build-up produced by an intermittent source.

Contaminants produced by a continuous source with the HVAC system off. With the HVAC system switched off, the concentration produced by a continuous source, at the initial stage of contaminant emission, is expected to increase rapidly (Case A). The rate of increase will then decline substantially until the concentration reaches the steady-state value (Case B). Figure 4 shows the concentration profile produced by a continuous contamination source measured in a closed room with the HVAC system turned off. The concentration reached the steady-state value after about 30 hours. This profile may be used to represent the contamination build-up in a building during a weekend when the HVAC system is turned off.

5.3 Meeting Room Ventilation

Meeting rooms are places with a relatively high density of sources that generate air contaminants intermittently. These rooms are usually installed as part of a fit-up project. The office spaces in which the meeting rooms are installed are typically equipped for the general ventilation adequate only for office workstation use. Additional ventilation must be provided to meet the requirements of the new higher population density.

The increased ventilation can be achieved by installing a supplementary ventilation supply for the meeting room. The supply of additional ventilation air can be controlled by a CO_2 sensor. In such situations, an additional temperature-control device with a reheat coil may be needed to prevent the room from over-cooling as a result of the increased ventilation.

Another method of providing more ventilation air is to install a transfer-air fan that supplies the meeting room with return air taken from the areas surrounding the meeting room. This fan can either be manually operated or controlled by a sensor, e.g. a CO_2 sensor.

6 Performance Indicators of General Ventilation

Several performance indicators for general ventilation processes are used by members of the HVAC industry. Some of them are more suitable for design purposes, some for operational purposes, and some for IAQ control/management. Two indicators — ventilation rate and occupant-generated CO_2 concentration — are discussed here.

6.1 Ventilation Rate

The Ventilation Rate Procedure, described in *ASHRAE Standard 62-1989, Section 6.1,* recommends ventilation rates for different types of buildings. For office buildings, the standard recommends 10 litres per second per person (L/s/person) of outdoor air of acceptable quality. The meaning of 'acceptable quality' is defined in the ASHRAE standard. The recommended ventilation rate is expected to achieve indoor air quality considered acceptable by most occupants, if no known sources of contaminants exist in the building, e.g. freshly installed materials that give off fumes, or smoking.

Using the Ventilation Rate Procedure, designers can easily calculate the total ventilation rate required for a building. This procedure is suitable for designing and commissioning HVAC systems, specifically for adjusting the position of the outdoor-air dampers to ensure that the outdoor-air supply rate complies with the standard. However, while the total ventilation rate for a building may be in accordance with that stated in the Ventilation Rate Procedure, the distribution of the ventilation-air supply to various parts of the building may not be adequate, i.e. proportional to the occupant density.

Measuring the ventilation rates at individual workstations or in designated HVAC zones in a large building, using currently available methods, is often prohibitively expensive and has probably resulted in the inadequate commissioning of many buildings. One promising method for assessing the adequacy of air distribution in office buildings is the measurement of the occupant-generated CO_2 concentrations at various locations throughout the building.

6.2 Occupant-Generated CO_2 Concentration

The Indoor Air Quality Procedure, described in *ASHRAE 62-1989, Section 6.2*, provides an alternative method to the one described in the Ventilation Rate Procedure for achieving acceptable air quality. The Indoor Air Quality Procedure provides a direct solution by restricting the concentration of all known contaminants to some specified acceptable levels and is, therefore, particularly suitable for commissioning or assessing the performance of the air-distribution system. The Indoor Air Quality Procedure stipulates that the concentration of CO_2 in office buildings must not exceed 1000 ppm.

For seated office workers (typically with a physical activity level of 1.2 *met* units) who produce CO_2 at an average rate of 0.3 L/min/person, at least 7.5 L/s/person of outdoor air are required to maintain the CO_2 concentration in the space at 1000 ppm or less.

> A *met* is the rate of energy production of the human body.
> 1 *met* = 58.2 W/m^2
> = energy produced per unit surface area of a seated person at rest

For office buildings, the occupant-generated CO_2 concentrations, which are usually controlled by the ventilation air, are proportional to the number of occupants. Thus, the measurement of actual CO_2 concentrations at individual workstations and in zones of an office building could be used to ensure that these areas are getting the required minimum amount of ventilation air. For workstations or zones where the CO_2 concentrations are greater than 1000 ppm, adjustments should be made to increase the ventilation rates. Appendix D of Volume II of the PWC/NRC IAQ Manual entitled *Controlling Indoor Air Quality: Ventilation Engineering Guide* (see References) includes a method and procedure for estimating the ventilation rates in individual workstations and zones which are based on measured CO_2 concentrations. The manual also contains a user-friendly computer program written for this purpose.

6.3 Relationship Between Ventilation Rate and Occupant-Generated CO_2 Concentration

The requirements for a properly designed and installed ventilation system include not only an adequate total ventilation rate but also an adequate distribution of ventilation air within the building, according to occupant distribution. The Ventilation Rate Procedure gives the minimum outdoor-air supply rate for the whole building. For example, in a building with an expected maximum occupancy of 100 people, the total minimum outdoor-air supply rate should be at least:

100 people x 10 L/s/person = 1000 L/s.

This procedure gives no indication of how the ventilation air is distributed within the building. However, the Indoor Air Quality Procedure, a performance-oriented method, places a limit on the variance in air distribution throughout the space. This is essential, particularly for variable air volume (VAV) systems, which distribute supply air (containing a certain quantity of outdoor air) in response to heating and cooling loads rather than to occupant loads. It is this latter type of load which should be used as the basis for calculating the ventilation-air requirements. The distribution of outdoor air is further complicated by the fact that the solar component of the heat gain in the building changes throughout the day, from one side of the building to the other.

6.4 Two Ways of Expressing Ventilation Rate

Sometimes the ventilation-air rate is expressed in terms of air changes per hour (ac/h). This approach is useful for design purposes and allows for the selection of heating and cooling equipment for a building when the exact number of occupants is not known.

The percentage of outdoor air required is another way of expressing the ventilation-air rate. This approach is useful to contractors involved in the installation of HVAC equipment for spaces for which the number of occupants is not known.

6.4.1 Air Changes per Hour

The number of air changes per hour always means the number of changes of outdoor air.

The ventilation rate of 10 L/s/person of outdoor air translates into approximately 0.5 ac/h for typical office buildings. In buildings with HVAC systems equipped with a free-cooling cycle, the air-change rate may, at times, be as high as 4 or 5 ac/h.

The term "free-cooling" is used to reflect the fact that sometimes during the year, the outdoor air has adequate cooling capacity to provide the cooling requirements for the building. This period of free-cooling occurs during spring and fall when the outdoor-air temperature is above 0°C but below the indoor-air temperature.

6.4.2 Percentage of Outdoor Air

In a typical office building, the ventilation rate of 10 L/s/person translates into 15 to 25 percent outdoor air. In buildings with HVAC systems equipped with a free-cooling cycle, the percentage can be as high as 100 percent, depending on the outdoor-air temperature and the cooling load of the building.

7 IAQ Standards

Two indoor air quality standards are applicable to office buildings; the Health and Safety Standard and the Acceptable Indoor Air Quality Standard.

The Acceptable IAQ Standard for office buildings is superior to the air quality requirement defined by the Health and Safety Standard to protect the health of industrial workers. In offices, the acceptable level of IAQ is defined as that which would provide an indoor environment conducive to the productivity of office workers.

7.1 Health and Safety Standard

The IAQ Health and Safety Standard has been prepared by the American Conference of Governmental and Industrial Hygienists (ACGIH). This standard has been adopted by all Canadian authorities having jurisdiction in the area of health and safety.

The ACGIH standard specifies two kinds of Threshold Limit Values (TLV): the Time Weighted Average (TWA) and the Short-Term Exposure Limit (STEL).

The TWA represents a mean value of the concentrations of a contaminant over a period of 8 hours. Exposure to a contaminant at concentrations below its TWA for 8 hours a day, 5 days a week, is considered safe. The TWA values represent daily doses of chemicals to which human beings can be exposed without long-term effects.

The STEL represents the concentration of a contaminant to which humans can be exposed for less than 15 minutes a day without experiencing long-term effects. The STEL is substantially higher than the TWA for the same chemical.

Both the TWA and STEL concentrations are based on incomplete scientific information. Since it is inconceivable that research to determine the relationship between the concentration of a chemical and its possible long-term adverse effects can ever be performed directly on people, scientists must resort to whatever indirect means and sources are acceptable and available.

It is important to recognize that TLV values are under constant review and that there is inadequate scientific knowledge regarding the long-term effects of both TWA and STEL concentrations of individual chemicals on human health. It is also important to note that there is no knowledge about the combined long-term effect of exposure to two or more of the indoor-generated contaminants even at very low concentrations.

7.2 Acceptable IAQ Standard

Acceptable indoor air quality is described by *ASHRAE Standard 62-1989* as air quality that is likely to be acceptable to at least 80 percent of the occupants. The other 20 percent of the occupants may be either partially satisfied or completely dissatisfied. This group may include, among others, environmentally sensitive people, as well as people who may be sensitized by either physiological or psychological stresses.

Whereas scientific knowledge is inadequate to fully support the ACGIH Standard specifying the health and safety level of IAQ, even fewer scientific facts support the acceptable level of indoor air quality as specified by ASHRAE. The acceptable level is established by a consensus based on a method that engineers successfully use in other engineering disciplines. This method uses a safety factor of ten, i.e. for a particular contaminant, the recommended level for the Acceptable IAQ Standard would be one tenth that of the Health and Safety Standard. Until more scientific knowledge becomes available, this method must suffice for controlling the IAQ of the office environment.

Rather than listing acceptable concentrations for all chemicals listed in the Health and Safety Standard, the ASHRAE standard for acceptable IAQ provides two main performance indicators; ventilation rates and the concentration of CO_2, previously discussed in Sections 6.1 and 6.2.

8 Control of IAQ by General Ventilation

Even in an office building in which the HVAC system has been properly commissioned to satisfy both the Ventilation Rate Procedure and the Indoor Air Quality Procedure, the IAQ in all workstations cannot be controlled at a constant level of quality. People tend to move from one workstation to another, or from one floor of the building to another. The commissioning process ensures that the building is adjusted for the distribution of occupants that may, in fact, seldom occur during a typical day.

Scientists at the National Research Council's Institute for Research in Construction have conducted several experiments to help understand the impact of changes in population density within the building on ventilation. For this purpose, they measured the average time it takes for the ventilation air to reach all parts of the occupied zone from the supply air registers.

They established that this time depends on:

- the volume of the building
- the supply-air flow rate
- the layouts of office furniture and privacy partitions
- the location of supply air registers.

They also found that in a relatively large office building with over 30 000 m^2 of floor area, it takes less than 20 minutes for the ventilation air to reach all parts of the building's occupied zones. The significance of this finding is that the general ventilation system will likely be able to accommodate people's movements within a building from one workstation to another, provided that such movements do not create any new densely populated zones and that the overall number of occupants remains relatively constant.

9 Normal Ventilation Regime of HVAC Systems

There are two modes of ventilation operation: normal and enhanced. The normal ventilation mode, i.e. the daily operating mode typically used, is discussed in this section (Section 9). The enhanced ventilation mode, used for control of the initial off-gassing phase that occurs immediately after the installation of new materials that emit chemicals, is discussed in the following section (Section 10).

The normal ventilation mode comprises two cycles:

1. the flushing cycle used prior to occupancy, i.e. before the employees come to work, and
2. the occupancy cycle used while they are at work.

9.1 Flushing Cycle

All newly installed building materials, furnishings and freshly painted walls emit contaminants. This emission is called off-gassing. After the initial off-gassing, the rate of emission of these contaminants levels off but continues nevertheless at a steady rate for a very long time.

The concentration of contaminants generated by the steady off-gassing is reduced by the general ventilation process, as long as the HVAC system is operating. Toward the end of each occupancy cycle, this concentration reaches its lowest level because the ventilation system has been operating throughout this period.

During the ensuing non-occupied hours, when the HVAC system is off, the concentration of off-gassed contaminants increases initially nearly linearly as shown in Figure 4. The rate of increase usually slows down after the concentration in the space reaches a certain value because of air leakage. (In an office building, the non-occupied period on a regular weekday is about 12 hours; for a regular weekend about 60 hours, and for a long weekend about 84 hours.)

The constancy of the off-gassing process may be affected by weather conditions, temperature, humidity, or by direct exposure to the sun. For purposes of determining the extent of a flushing cycle, however, such factors can be overlooked.

ASHRAE Standard 62-1989 offers a method of determining the extent of the flushing cycle. To use this method, the values of the initial concentration and the contaminant generation rate are required. Since such information is not readily available, this method has a limited practical application. A pragmatic method is offered here.

Table 1 shows the amount of outdoor air required to dilute the concentration of air contaminants to a certain level. One air change means that all the air in a building is completely replaced once by outdoor air. Two cases are presented here: a building with perfect mixing and a building with very poor mixing. The condition of most buildings is likely to fit somewhere between these two extremes.

Table 1: Reduction of Concentration of Contaminants

number of air changes	concentration (%) of contaminants:	
	perfect mixing	poor mixing
0	100.0	100.0
1	36.8	60.6
2	13.5	36.8
3	5.0	22.0
4	1.8	13.5
5	0.7	8.2

If it is important to know the degree of mixing in a particular building, a tracer gas test should be conducted. The degree of mixing can also be expressed as *ventilation effectiveness*. (However, the scientific community is still debating the exact definition of this term and how to measure it in an actual workstation in an office building.)

Generally, buildings with all-air and constant volume systems have better ventilation effectiveness than buildings with VAV or air-and-water systems.

Special attention must be paid to VAV systems. For purposes of IAQ control, each VAV box must be equipped with a stopper to prevent the box from closing beyond a pre-determined minimum position that, regardless of the heating or cooling load, satisfies the ventilation requirements in the area served by the VAV box.

9.1.1 Determination of the Outdoor Air Supply Rate for Flushing

The concentration of air contaminants in a building can be expected to increase rapidly in the period immediately following the shut-down of the HVAC system at the end of a regular working day. The maximum concentration reached depends mainly on the length of the shut-down period, the emission-source strength, and the airtightness of the building envelope. For an airtight building, the contaminant concentration is expected to increase linearly. For a relatively leaky building, the contaminant concentration would increase along a curve shown in Figure 4. Thus, the amount of outdoor air required to reduce the contaminant concentration to acceptable levels depends on the concentration level reached when the HVAC system has to be re-started at the beginning of the workday, in preparation for the arrival of office workers.

The outdoor-air changes required are determined by the following procedures: if the contaminant concentrations, both at the end of a scheduled shut-down and during working hours, are known, the number of air changes of outdoor air needed for the flushing period can be determined from Table 1. Since such information is often not readily available and since each building is unique, a trial-and-error method has to be used. For most buildings, about 2 air changes of outdoor air are adequate to dilute the contaminant levels after a scheduled weekday shut-down to levels that are acceptable for working hours. Therefore, 2 air changes are recommended for the flushing period after a scheduled weekday shut-down. The number of air changes can be increased or decreased, depending on the reactions of the occupants.

The contaminant build-up is expected to be greater for a regular weekend and still greater for a long weekend than for a normal weekday. More air changes are needed to reduce the contaminant concentration to the same levels achieved for working hours following weekday shut-downs. Since the contaminant build-up rates for most buildings are expected to follow a pattern that falls between that shown in Figure 4 and a linear function (the worst case), it can be estimated from Table 1 that 2 times the number of air changes used for weekday flushing are required for a regular weekend and 2.5 times that number for long-weekend flushing.

9.1.2 Satisfactory Flushing Cycle

To establish the appropriate number of air changes for flushing, it is necessary to involve the occupants. They should confirm whether they find the indoor air fresh upon their arrival at the building. This may take a long time to determine, but this time should not be considered wasted, since it provides an opportunity to build trust between the occupants and the property management/building operation staff. This trust is an important element of being able to provide acceptable indoor air quality.

9.1.3 Start-up Time

The established number of air changes needed for an acceptable flushing cycle must then be translated into the starting time of the HVAC system. When the outdoor conditions are favourable, i.e. during the spring and fall when the outdoor air is above freezing, the established air changes can be provided in a much shorter time because a higher percentage of outdoor air can be brought in. For example, if the number of established air changes is three, the operator can adjust the ventilation system to deliver 3 ac/h for 1 hour, instead of 1 ac/h for 3 hours. During spring and fall, and even on cool summer mornings, it is possible to use a shorter flushing cycle than that required on a typical winter or summer day (when the outside air is either too cold or too hot to be introduced into the building without treatment). During colder weather, the percentage of outdoor air required for a flushing cycle depends on the available heating capacity. It should be the governing factor in establishing the most energy-efficient start time for HVAC systems. (A proposed procedure to determine the appropriate start time is given in Section 11.)

This information can be prepared for the use of building operators in the form of tables and graphs. It could also be programmed into the building computer or energy management and control system (EMCS), as it is known in the industry.

9.2 Optimization of Flushing Cycle

In some buildings, it may be more effective and energy-efficient to consider splitting the flushing cycle into two or more periods; one period that immediately follows one occupancy cycle, another that immediately precedes the next one, and yet another that occurs between the two cycles.

The optimal times for these periods of flushing may be determined by the cleaning schedule used for the building, the weather conditions during "silent" hours, off-peak power rates, or extended hours of occupancy, either during evenings or on weekends.

9.3 Occupancy Cycle

During the occupancy hours, the HVAC system should be in its occupancy cycle. During this mode, the HVAC system must supply at least the minimum ventilation rate of 10 L/s/person of outdoor air.

During fall and spring, when cooling can be derived from the colder outdoor air (free-cooling), the cost of ventilation is low, because no energy is needed to run the refrigeration equipment. During these seasons, the ventilation rate can be higher than the required 10 L/s/person.

During summer, when cooling is provided by chillers, the cost of ventilation is higher because of the amount of energy needed for the conditioning of the warm, and often humid, outdoor air. Similarly, during winter, energy is required to heat the ventilation air. Instead of supplying a constant amount of ventilation air, changing the ventilation rate based on the number of occupants inside the building at a particular time is a cost-effective measure under these conditions. A ventilation demand controller is a device that does exactly that: it adjusts the total outdoor-air supply rate automatically according to the number of occupants in the building.

In buildings without the ventilation demand controller, the recorded daily CO_2 concentration curve resembles the back of a two-humped camel (see Figure 2). Typically, at about 7 a.m., the indoor CO_2 concentration increases from the outdoor level, reaching the first peak concentration at noon. The level subsequently decreases slightly during the lunch period and then increases again to reach an approximate steady-state concentration at about 2 p.m. The CO_2 concentration decreases steadily after 4 p.m., reaching the outdoor level at about midnight. At no time, however, should any point on this curve be above the concentration that has been calculated as the steady-state concentration for a particular building with a given supply-air system.

10 Control of Off-gassing — Enhanced Ventilation Cycle

After installation of certain materials, air contaminants are generated at an escalating rate which, however, diminishes with time. Usually, the decay process reaches a steady-state off-gassing rate in several days or weeks, depending on the type of material. The period between the time of installation and the time when the steady-state off-gassing rate is reached is known as the initial off-gassing phase. This is also the period during which additional ventilation is needed to dilute the large amount of contaminants generated.

During this phase, the generation rate of air contaminants depends on the type and quantity of the material installed and the elapsed time since its installation. The concentration normally decays exponentially, as shown in Figure 5.

By using information about the type, quantity and emission rates of the materials to be used, a ventilation engineer should be able to establish the additional ventilation rate that will be needed and thus to predict the duration of the enhanced ventilation cycle.

After the installation, the ventilation engineer should be able to improve the estimate of the duration of the enhanced ventilation cycle from measurements of the contaminant concentrations taken on at least two separate occasions. In many cases, this process may need to be repeated several times to achieve reliable and energy-efficient control of IAQ.

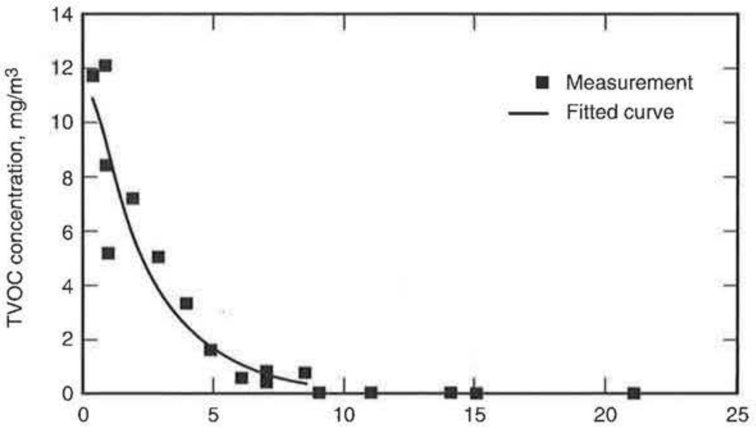

Figure 5. *TVOC concentrations in an office space, with background concentrations subtracted*

The necessary steps required to predict the duration of the enhanced ventilation cycle are described in the document *Controlling Indoor Air Quality: Ventilation Engineering Guide* (see References). This document also contains a diskette with a computer program written for this purpose.

Although most of the off-gassing products can be effectively removed from their place of origin by operating the HVAC system in an enhanced ventilation mode, some of them may migrate through the building. In newly constructed buildings, their migration may not be noticeable, since the off-gassing products are generated throughout the building.

In existing buildings, the initial off-gassing is usually localized. Off-gassing products are typically generated where an old carpet is being removed, a new carpet laid, new furniture moved in, or walls painted. Even a minute amount of off-gassing products migrating through the building can be easily detected by its occupants. As long as this amount is minute, it may actually be perceived by occupants as a sign of good house-keeping. Off-gassing products may accumulate to objectionable levels, however, unless the migration process is properly controlled. Therefore, precautionary measures should be taken to keep off-gassing products from migrating from their place of origin to other occupied parts of the building.

To better understand this process of migration of off-gassing products through a building, the Institute for Research in Construction developed a computer program that predicts the spread of a contaminant from the source to the surrounding areas under various weather conditions. The program also assesses the effectiveness of various ventilation strategies for removing contaminants: for example, venting through an open window or a vertical shaft.

The computer program indicates that the most effective migration control can be achieved by sealing off the return-air opening on the affected floor, while keeping the supply air coming into the affected floor and removing the air either through a smoke shaft, a window opening or a stair shaft that opens directly to the outside. These means of control are effective, provided that the pressures induced by the stack effect and wind do not work against the removal of the contaminants. In winter, for example, contaminants on lower floors will be pushed to upper levels because of the stack effect. The stack-effect mechanism can be used to advantage, however, by venting the contaminants through a vertical shaft, e.g. a stair shaft or, under windy conditions, by venting the contaminants through a leeward window thus preventing their spread to surrounding areas.

11 Best Practice

The following steps should be taken to establish and implement the most effective means of operating HVAC systems to achieve reliable and energy-efficient control of IAQ.

Step 1: Provide all local sources of air contaminants, as well as meeting rooms and board rooms, with dedicated ventilation systems.

Step 2: Adjust the minimum position of the outdoor-air damper on each HVAC system to provide an average ventilation rate of 10 L/s/person of outdoor air and re-commission the HVAC distribution system to ensure that the CO_2 concentration is not greater than 1000 ppm in any occupied workstation. This can be achieved by the proper balancing of the HVAC system and, possibly, by the installation of a ventilation demand controller that adjusts the minimum position of the outdoor-air damper automatically.

Step 3: Establish the number of air changes required for flushing on the morning after a regular work day, either by using Table 1 or by beginning with two air changes. Use 2 times the air-change value established for the flushing cycle after a work day to determine the flushing cycles for a regular weekend and 2.5 times that value for a long weekend.

Step 4: Convert the number of air changes established in Step 3 into the running time of the HVAC system for flushing cycles following working days, regular weekends and long weekends. For example, a requirement of two air changes translates into 4 hours running time for a ventilation rate of 0.5 ac/h, or 2 hours running time for a ventilation rate of 1 ac/h. Note that running time should be determined as a function of outdoor-air temperature.

Step 5: Determine the start-up time for the HVAC system based on the running time established in Step 4; program this information into the EMCS.

Step 6: By close and on-going communication with the occupants concerning their perception of the acceptability of IAQ, modify the number of air changes that was initially selected in Step 3 to establish the most suitable air-change requirement for the flushing cycle for the building.

Step 7: Inform the occupants regularly about compliance with the ventilation strategy. Also, inform them immediately of each non-compliance and its nature, and establish regular communication concerning the status of any remedial actions.

Step 8: Where renovation, remodelling or repair work is scheduled, establish and implement the best method of migration control of possible off-gases before such work begins and implement an enhanced ventilation mode during the initial off-gassing process. When the off-gassing process reaches its steady state, revert to a normal ventilation mode by following Steps 1 through 7.

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