CONTROLLING INDOOR AIR QUALITY

Cette publication est aussi disponible en français.

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This document was written by E.G. Plett, P.Eng., Sc.D., Professor at Carleton University. Its development was led jointly by F. Vaculik, P.Eng., M.E., Chief, Operation Maintenance and Commissioning, Public Works Canada, and C.Y. Shaw, P.Eng., Ph.D., Senior Researcher, National Research Council of Canada.

The document was reviewed by the following people from Public Works Canada: G. Kerr, B.Sc., Ph.D., Environmental Chemist, G. Laszlo, P.Eng., Chief, Mechanical Engineering, E.J. Newman, P.Eng., Director, Technical Services, and D.W. Patton, P.Eng., Director, Property Management Policies, Best Practices and Product Development.

VENT COMPUTER PROGRAM

Ventilation rates for normal ventilation and enhanced ventilation regimes in office buildings discussed in this Guide can also be calculated on a personal computer. The computer program VENT written for this purpose is available from the PWC Documentation Centre, Sir Charles Tupper Building, Riverside Drive, Ottawa, Ontario, K1A 0M2, telephone (613) 736-2146.

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SECTION 6

APPENDICES

1.0 INTRODUCTION

Control of indoor air quality (IAQ) in office buildings can be achieved through effective application of ventilation engineering. This document is designed as a guide to be used by:

- ventilation engineers as they implement indoor air quality control solutions, both at the time office building projects are implemented, and when the office buildings are occupied by tenants;
- project managers and property managers as they oversee the provision of ventilation engineering services; and
- building operators as they participate in the day-to-day operation of the facility.

This document is the second of two on the subject of indoor air quality that have been jointly prepared by Public Works Canada and the National Research Council of Canada. The first, entitled "Managing Indoor Air Quality," was prepared to help property managers proactively identify IAQ problems. With this second document, such problems can effectively be corrected.

2.0 INDOOR AIR QUALITY CONTROL

2.1 Participants in Indoor Air Quality Control

Three distinct groups participate in the delivery of acceptable IAQ to tenants, either directly or indirectly. They are:

Operators

This group is made up of people with very diverse backgrounds, headed by a property manager (PM). The PM is the principal contact with the tenant(s), and is responsible for the day-to-day delivery and control of indoor air quality. When necessary, the PM calls on a ventilation engineer from an in-house or external technical service organization. Ventilation engineers are expected to offer the range of services described in this document.

Implementors

This group includes designers, contractors, and suppliers of building equipment and material. They are expected to provide a facility which can accommodate a reasonable range of ventilation strategies; only seldom do they become involved with the selection and implementation of these strategies once the facility has been put into operation.

Building Scientists

This group is concerned with two separate issues:

- the performance of the physical building elements; and
- the psychological or physiological impact of these elements on the occupants.

Individuals within this group work in very narrow and highly specialized areas, and only a few are involved with both issues. This may result in differences in perception and approach.

2.2 Interaction of the Participants

Generally, the parties involved with IAQ-related issues tend to work in isolation from each other, with each group apparently adhering to a different set of rules for survival. Consequently, there are several different approaches to solving IAQ problems, each with its own specific jargon. This document, like the first one, "Managing Indoor Air Quality," provides a common basis for interaction among the participants. It proposes a common language that can be used and understood by all three participant groups and the end-users of IAQ, the tenants.

2.3 Pro-active Control of Indoor Air Quality

In existing buildings, where off-gassing from freshly installed materials has effectively reached a steady state, ventilation engineering services are normally provided in a reactive way, i.e. to correct problems as they arise. On the other hand, in newly constructed, newly renovated, or newly leased buildings, ventilation engineering services should be provided in a pro-active way. In Public Works Canada, the Project Delivery System (PDS) provides such a delivery framework.

Appendix A provides project managers with a guide to obtaining pro-active ventilation engineering services in the most effective way. By following the PDS guide, project managers will avoid creating less-than-satisfactory IAQ conditions that in some cases result in a building being labelled with "sick building syndrome."

At the conclusion of the PDS cycle, the building enters into its service life cycle. During this cycle, changes to the use of the building occur on a regular basis. Substantial changes are implemented according to the PDS, which includes the involvement of a project manager.

In such cases, it is expected that ventilation engineering services will be properly provided. However, when smaller changes are instituted either by tenants or by the property management staff, the ventilation engineering services may be lacking, and complaints about IAQ may occur. In such cases, the ventilation engineering services can only be provided in a reactive way.

2.4 Investigation Strategies

Often, complaints from tenants are the first indication that problems with indoor air quality may exist. To help property mangers distinguish between minor local incidents and significant general complaints, PWC recommends a three-level approach to handling tenants' complaints.

Level I

Level I investigation should be carried out by property managers in consultation with building operators. It includes documenting and analyzing occupants' complaints, and a walk-through inspection of the building. If the causes cannot be identified, a Level II investigation will be initiated. The first PWC/NRC manual, "Managing Indoor Air Quality," has been prepared to assist in Level I investigations.

Level II

Level II investigations should be conducted by ventilation engineering practitioners. This level involves the physical investigation of the work space in question. The steps outlined in Section 3 will help evaluate the physical aspects of the environment in the occupied space.

If the results of Level II investigations are inconclusive, a Level III investigation may be initiated.

Level III

Level III investigations should be conducted by a team of building scientists, ventilation engineers, and/or medical experts. This approach involves both physical and psychological investigations, and may use tools and measurement methods that are still under research and development. Part of this strategy can involve conducting an office environment survey. A nine-page PWC questionnaire is available for this purpose, which includes questions relating to:

- the various symptoms occupants may be experiencing;
- the frequency of these symptoms;
- the perceived environmental conditions in the work space;
- the nature of work done by the individual; and
- the individual's level of satisfaction with the work in which he/she is engaged.

Guidelines for conducting Level III investigations will be prepared when the required tools and methods have been reasonably well developed.

2.5 Issues Underlying Acceptable Indoor Air Quality

Certain words and phrases used in discussions of IAQ may convey different meanings to different people. Before any meaningful dialogue can take place, agreement on these terms should be established.

A fundamental question relating to IAQ is whether or not a correlation can be found between the quality of the physical environment and human physiological and psychological responses. The question is very complex, and building scientists, together with medical professionals, will need to devote substantial time and effort to finding the answer.

In "Managing Indoor Air Quality," a concept of a continuum of human perception of IAQ is introduced. (See Figure 1.) The concept distinctly separates "healthy" and "unhealthy" conditions into two zones, separated by the health and safety standards of the Occupational Safety and Health Administration (OSHA) and American Conference of Governmental Industrial Hygienists (ACGIH). Within the "healthy" zone, as the concept clearly shows, is a smaller area which has been identified by as the comfort zone. The conditions in this zone are conducive to productivity, and are specified by ASHRAE Standard 62-1989.

Some terminology relative to the quality of the physical environment is still insufficiently clear, as explained below.

Ventilation Effectiveness

The relationship between the local ventilation process applied to control air contaminants in individual work stations, and the general ventilation process applied to control air contaminant sources distributed throughout the entire occupied space, is not yet well enough understood to fully document at this time.

An objectively measurable definition of ventilation effectiveness is needed. This definition must include the degree of penetration of outdoor air into individual work stations, and the effectiveness of the purging process at points where air is being inhaled, as some of the contaminants are removed with the exhaust air. ASHRAE is in the process of developing a standard on ventilation effectiveness which is expected to address this question.

Off-gassing

Although off-gassing has long been recognized as a phenomenon that adversely affects IAQ, it has never been dealt with in a systematic way. Section 4 of this document provides a practical approach to the control of air contaminants generated by off-gassing, through an enhanced ventilation cycle.

There is still a need for more complete documentation of the off-gassing process, in order to clearly define the behaviour of both sources and sinks, or primary and secondary sources of contaminants, and how these affect the distribution of air contaminants over time.

It is not reasonable to await full explanations of these areas of uncertainty before taking steps to provide satisfactory IAQ to office building tenants. The practice now most clearly understood should be followed, and if further insights suggest a change of practice, the procedure should be modified accordingly.

2.6 Sources of Air Contaminants

Air contaminants in an office building usually originate from any of three sources:

- people;
- processes (such as photocopying);
- building materials and furniture.

A brief discussion of each of these general categories follows.

People

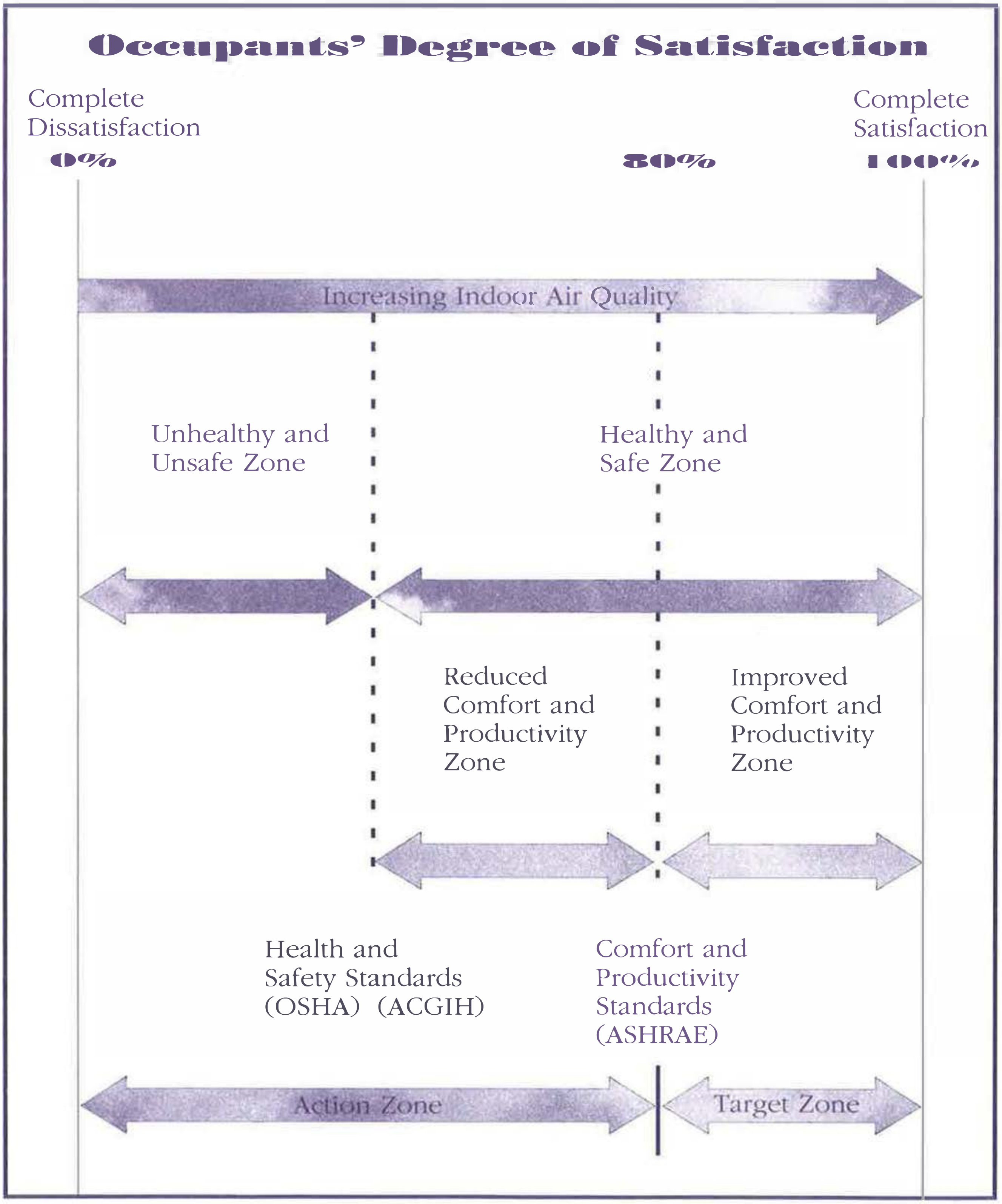
Our normal respiratory process removes oxygen from the air and contributes carbon dioxide and water vapour. The rate at which this occurs varies with the level of physical activity of individuals. Following are approximate average rates of CO_2 production attributed to several levels of physical activity.

■ people at rest	0.0036 L/s (0.0075 cfm)
■ people doing desk work	0.0050 L/s (0.010 cfm)
■ people doing bench work	0.0072 L/s (0.015 cfm)

Generally, more vigorous activity levels result in higher rates of CO_2 production.

Conceptual Relationship Between Health and Safety, and Comfort and Productivity Standards for Indoor

AIR QUALITY AND CLIENT SATISFACTION



People also contribute other types of contaminants, such as body odours, but since carbon dioxide is the most easily quantified of all the contaminants produced by people, its concentration is used to determine the adequacy of outdoor ventilation air.

Processes

Processes which can contribute to air contamination include copying machines, and any other office equipment that uses volatile organic chemicals (VOCs).

Some copying and printing machines generate VOCs, which, in higher concentrations, may have an adverse effect on IAQ. Recent research indicates that normal ventilation rates do not always control these VOCs effectively, so suitable local exhaust arrangements should be made.

Cleaning solvents are another source of contaminants, and while they are normally administered during non-office hours, their effects could linger unless the ventilation system remains on during the time they are being used.

Fossil-fuelled heating systems and automobiles are major sources of air contaminants, but if the utility room and parking garage are adequately ventilated and properly separated from the rest of the building, they should not contribute to the contaminants in the office space.

Building Materials and Furniture

New building materials often contribute significantly to local air contaminants. (This is dealt with at greater length in Section 4.) Even "mature" materials will off-gas to some degree, as evidenced by the odour sensed in a room that has been sealed for a period of time. Under normal operating conditions, the contaminants produced by building materials and furniture will be adequately purged, if the ASHRAE standard for ventilation rate is followed.

It should be considered, however, that materials such as carpeting and furniture fabric can absorb air contaminants produced by other sources, then re-emit them later. Additional ventilation, either before or after normal working hours, will help to remove contaminants from these secondary sources.

2.7 Approaches to Indoor Air Quality Control

Two general approaches to achieving acceptable indoor air quality are considered:

Source Control

Considerable progress has been made in controlling the air contaminant sources in the industrial environment. While the opportunity for source control is somewhat more limited in an office setting, it can still have an impact. For example, selecting a photocopier that emits few contaminants would be effective.

When renovations to office space involve painting, it is preferable to use latex paints rather than oil-based products, since the latex paints emit lower amounts of volatile organic compounds. On a positive note, a major source of air contamination has been eliminated with the relatively recent ban on smoking in federal workplaces.

Source control alone, however, cannot be expected to provide the desired air quality. Occupants need photocopiers, office renovations will continue, and people who occupy the space will themselves remain a major source of air contaminants. Consequently, ventilation must play some role in controlling indoor air quality.

Ventilation

Ventilation is the other way of controlling IAQ. It is the process of bringing outdoor air into a building to displace exhausted air that contains contaminants. The most common form employed is general ventilation, in which ventilation is applied to the entire building.

With general ventilation, part of the air in the space is replaced with outdoor air which contains lower or no concentrations of undesirable components. Normally, by design, only a small portion of the air supplied to the space is "new." Because this new air is mixed with return air, which is of acceptable quality since it came from a space with acceptable IAQ, the quality of the supply air is better than the threshold of acceptability by the exact difference that is necessary for control of the air contaminant concentration in the space.

Another form of ventilation, local exhaust, is more effective in ridding the space of fumes, by direct venting to the outdoors. This technique is used to exhaust air from washrooms, storage rooms, janitor closets, kitchens, etc. directly to the outdoors. The air making up for the exhausted air may enter by infiltration, or preferably, by a more active means such as a properly designed ventilation system.

Conclusion

In most cases, a combination of source control and ventilation appears to be the best method of achieving acceptable air quality in office buildings. Subsequent sections of this document further explain the process and effects of ventilation as a means of air quality control.

3.0 NORMAL VENTILATION

The normal ventilation strategies described in this section apply to buildings which have not been recently renovated or refitted, and which have not had new materials such as paint or carpets added.

3.1 Delivery Process

This section suggests a general approach for assessing a building's ability to provide good air quality, and for implementing corrective measures where needed. Refer to Section 4 for information on the enhanced ventilation strategy to be used in buildings with freshly installed new materials.

At Level II, as defined in 2.4, the following steps for delivery of ventilation engineering services are recommended:

1. information gathering;
2. walk-through inspection;
3. initial review;
4. detailed measurements of temperature, relative humidity and CO_2 concentration;
5. measurement of air change rates and ventilation air flow distribution;
6. identification and measurement of contaminants;
7. interim review;
8. establishment of the relationship between contaminant concentration and air change rates;
9. design and implementation of ventilation solution;
10. commissioning;
11. monitoring of compliance with ventilation requirement;
12. final review and report.

Note: Depending on the policies and regulations related to investigation of IAQ complaints, and on the availability of instruments and experience, some of the measurements must be performed by highly specialized and/or authorized personnel.

These steps are described in detail in Appendix B. In many cases, all 12 steps need not be taken to effectively implement a remedial action. For example, if a solution is identified after steps 2 and 3, steps 9 and 10 may follow. Then, if the identified, implemented, and commissioned solution is effective, steps 11 and 12 should complete the delivery cycle. Otherwise, another solution must be sought by returning to step 4, then 5, 6, and 7, then jumping once again to steps 9 and 10. This approach is considered to be the most effective.

3.2 Common Causes of IAQ Problems

Problems with indoor air quality are most often linked to:

a) inadequate temperature and humidity control;
b) inadequate ventilation;
c) chemical contamination; and
d) microbiological contamination.

Experience in testing office buildings has shown that chemical contaminants are normally present at concentrations far below the limits established for industrial workers, so detailed measurement of such contaminants rarely reveals a problem. Consequently, the process of identifying and solving potential problems as noted in Subsection 3.1 is recommended.

3.3 Normal IAQ Requirements

The criteria against which air quality or HVAC system performance are to be assessed include ASHRAE Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality," ASHRAE Standard 55-1981, "Thermal Conditions for Human Comfort," and, where applicable, environmental conditions in the occupancy agreement that supplement or override these standards.

These criteria ensure that the quality of the indoor environment is adequate from a comfort or productivity perspective, and this in turn automatically ensures that health and safety requirements will be met.

Complying with the health requirements in office buildings is relatively easy. From the comfort or productivity perspective, on the other hand, compliance is more difficult. It is virtually impossible to satisfy 100 percent of the people 100 percent of the time. For this reason, ASHRAE provides a range of conditions aimed at satisfying 80 percent of building occupants.

The ASHRAE standards specify conditions that should be maintained in occupied spaces as follows:

■ Minimum outdoor air supply rate:	10 L/s per person
■ Air temperature:	20 – 27° C
■ Relative humidity:	20 – 70 percent
■ Maximum CO_2 concentration:	1000 ppm

The criteria do not specifically address the issue of air flow distribution, other than to cite the minimum outdoor air supply rate per person and the maximum concentration of CO_2 in a work station.

3.4 The Critical Work Station Concept

In office buildings, air distribution systems that perform the function of general ventilation systems are generally designed to meet thermal load requirements, both heating and cooling. They are therefore not linearly related to the distribution of personnel in the office space. ASHRAE Standard 62-1989 introduces a method of calculating the total outdoor air supply that compensates for discrepancies in the distribution of heating and cooling loads, and the number of people present. This method is based on a concept of the critical work station, and is explained in Appendix C.

3.5 Compliance with IAQ Requirements

ASHRAE Standard 62-1989 prescribes two procedures for assuring compliance with IAQ requirements. A brief description of these procedures follows.

Ventilation Rate Procedure

The ventilation rate procedure is based on solving equation (6-1) of ASHRAE Standard 62-1989. Manipulation of this equation, which is described in detail in Appendix C, is time consuming.

Note: A computer program called VENT has been written to speed up the use of equation (6-1) of ASHRAE Standard 62-1989 when applying this procedure. The tutorial to this program explains how it is to be used to calculate total ventilation rate, concentration of CO_2, air changes per hour, and average work station rates per person. It also shows the user how to assess the impact of each variable.

To effectively use the ventilation rate procedure, careful air flow rate measurements must be made at all main branches of the supply duct, at all supply air outlets, and at outdoor air intakes — a rather impractical task given the large number of locations. Without these measurements, however, one cannot be certain that the correct amount of outdoor air is being delivered. This uncertainty is increased in buildings with variable air volume systems.

Consequently, the ventilation rate procedure is not only impractical, but also inaccurate. In fact, it provides only an indirect solution to indoor air quality control.

For description of the measurement in support of the ventilation rate procedure see Appendix G.

Indoor Air Quality Procedure

ASHRAE Standard 62-1989 suggests a second procedure, which is based on the level of contaminants found in the air. This more direct method involves measuring the contaminant concentrations, and ensuring that the flow of outdoor air is sufficient to keep these concentrations at an acceptably low level.

This method is based on the premise that keeping the major occupant-produced contaminant at an acceptably low level (through purging and dilution with outdoor air) will result in all other contaminants being maintained at acceptably low levels. Hence the use of the CO_2 method is established.

This method therefore uses CO_2 as a surrogate indicator of indoor air quality. If the CO_2 concentration is monitored and found to meet the standard in every work station, then it is de facto established that the required amount of outdoor air has been supplied to every work station.

According to the ASHRAE Ventilation Standard, occupants must not be exposed to more than 1.8 g per cubic metre or 1000 ppm of CO_2 ON AVERAGE over an eight-hour period. Clearly, this criterion is met if the CO_2 concentration does not exceed 1000 ppm at any time during the day, but if it does, a time weighted average exposure would need to be computed.

It is relatively easy to ensure compliance with the ASHRAE Standard 62-1989 by measuring CO_2 concentration throughout the day. When measuring individual work stations, care must be taken however that the work station is not occupied by more than one person for an extended period of time as this would obviously affect the reading.

Application of this procedure for measurement purposes is described in Appendix D. An automatic control method based on this procedure is described in Section 5, Ventilation Demand Controller.

Conclusion

Of the two procedures prescribed by ASHRAE Standard 62-1989, the Indoor Air Quality procedure is the easier and the more direct way of verifying compliance with normal ventilation requirements in office buildings.

3.6 Air Distribution

The above procedures are intended to ensure adequate intake of outdoor air into the whole building. To achieve good ventilation and IAQ, it is also necessary to ensure adequate air distribution to and within each work station.

Good air distribution to each work station is achieved by good air balancing. Air distribution within work stations affects ventilation effectiveness: the better the air distribution, the more effective the dilution process, and the better the IAQ control.

Supply air outlets are expected to provide all the kinetic energy to the supply air that is necessary for good removal of contaminants. However, it is not always possible to achieve good air circulation by adjusting supply air velocity and direction only. The physical configuration of the work station also needs to be taken into account. In some cases, circulation can be improved by raising partitions off the floor. Where none of the above good ventilation engineering practices result in an adequate circulation, an additional kinetic energy source, i.e. desk or ceiling fan, may need to be considered. This may be especially true in buildings with variable air volume systems, where the supply outlet velocity varies, and therefore cannot be adjusted for only one velocity.

Although there are sophisticated methods that can be used to measure other aspects of IAQ, there are but few rather primitive tools that the ventilation engineer must use to measure air distribution within a work station. These are the smoke pencil, tape and stop watch. These tools can be used to determine air motion at the desk level, which should be between 5 to 15 cm/s. It should be noted that hot wire anemometers are not accurate within that low velocity range.

There is still much to be learned about air distribution with respect to ventilation effectiveness. ASHRAE is in the process of writing a standard on ventilation effectiveness that is expected to provide more professional guidance to ventilation engineers.

3.7 Maintenance Considerations

Many IAQ complaints have been found to be maintenance-related. Inadequate procedures or inadequate maintenance efforts can cause problems with bacteria, fungi, dust, etc. Proper maintenance of air filters, humidifiers, coil dripping pans, coupled with appropriate water treatment programs, can eliminate many of these problems.

Public Works Canada is using preventive maintenance procedures based on its own experience, as well as the best practice of the industry. These procedures are designed to control maintenance-related IAQ problems; however, there are still many questions that need to be answered. Research in this area is not progressing fast enough. The industry needs to develop effective, but not excessive, maintenance procedures that would result in effective and efficient control of IAQ.

4.0 ENHANCED VENTILATION STRATEGIES

The enhanced ventilation strategies described in this section apply to buildings which have been recently renovated or refitted, i.e. to which new materials such as paint and carpets have been added.

4.1 Delivery Process

For buildings with freshly installed materials, the following process of ventilation engineering services delivery is recommended:

1. identification;
2. definition of ventilation requirements;
3. design and implementation of ventilation solution;
4. monitoring;
5. change-over to normal ventilation strategy.

These steps are described in detail in Appendix E.

4.2 Types of Contaminants Introduced by Construction or Renovation

The type of compounds that are off-gassed depends on what types of materials are brought into the building. A brief description of some common contaminants is listed below.

Formaldehyde:

Formaldehyde is a colourless gas. In high concentrations, it has a pungent, suffocating odour. This compound is used extensively as an ingredient in various building materials, particularly in materials containing resins, such as phenolic resins. Consequently, it is present in higher quantities in areas that have been newly furnished, renovated, or constructed. Formaldehyde is present either from direct off-gassing from new materials, or as a result of chemical release during the curing process of materials

Table 4.1 Formaldehyde Emissions from a Variety of Construction Materials, Furnishings and Consumer Products

Product	Range of Formaldehyde Emission Rates $\mu g/m^2/day$
Medium-density fibreboard	17,600 – 55,000
Hardwood plywood panelling	1,500 – 34,000
Particleboard	2,000 – 25,000
Urea-formaldehyde foam insulation	1,200 – 19,200
Softwood plywood	240 – 720
Paper products	260 – 660
Fibreglass products	400 – 470
Clothing	35 – 570
Resilient flooring	<240
Carpeting	none – 65
Upholstery fabric	none – 7

Source: Godish, T., *Indoor Air Pollution Control,* Lewis Publishers, Chelsea, Michigan, 1989.

containing such resins. Table 4.1 gives an indication of the relative importance of some sources of indoor contamination by formaldehyde.

Volatile Organic Compounds (VOCs):

This designation encompasses a large number of compounds. Table 4.2 lists the 24 (of over 200 detected) nonaliphatic compounds (non-fatty hydrocarbons) most commonly found in office buildings. Several hundred aliphatic hydrocarbons are also to be found. The hydrocarbons found include such groups as:

- aliphatics
- aromatics
- alkylbenzenes
- ketones
- polycyclic aromatics
- chlorinated hydrocarbons

In newly constructed buildings, some of these compounds may have initial concentrations as much as 600 times the concentrations usually found in buildings containing mature materials only. The initial concentration may or may not be in excess of acceptable long-term exposure levels.

As with most contaminants, even if the initial concentration is above acceptable levels, short-term exposures are unlikely to pose a substantial health threat. They may, however, result in discomfort or even temporary irritation to individuals exposed to them.

The composition of the products listed in Table 4.3 would determine the VOCs released, although the same type of product by a different manufacturer may result in different VOCs.

4.3 Off-gassing Processes

The physical/chemical processes which produce gaseous contaminants in the air after installation of new materials will depend very directly on the material and the products they produce. It is generally accepted that the process is time dependent, and therefore the amount of off-gassed contaminants in time can be plotted in form of an exponential curve representing decay of concentration. (See Figure 2.)

Table 4.2 Twenty-four Nonaliphatic, Organic Compounds Most Commonly Found in Public Access Buildings

Acetone	1,1,1-Trichloroethane
Benzene	Trichloroethylene
Toluene	Propylmethylbenzene
Xylene	Dichlorobenzenes
Styrene	Nononal
Ethylbenzene	Diethylbenzenes
Ethylmethylbenzenes	Methylene chloride
Trimethylbenzenes	Chloroform
Tetrachloroethylene	Decanal
Naphthalene	Acetic acid
Methylnaphthalenes	Propylbenzene
Dimethylbenzenes	Trichloroflouromethane

Source: Godish, T., *Indoor Air Pollution Control*, Lewis Publishers, Chelsea, Michigan, 1989.

Table 4.3 Volatile Organic Compounds in Building Materials

Material	Major VOCs Identified
Latex caulk	Methylethylketone, butyl propionate, 2-butoxyethanol, butanol, benzene, toluene
Floor adhesive	Nonane, decane, undecane, dimethyloctane, 2-methylnonane, dimethylbenzene
Particleboard	Formaldehyde, acetone, hexanal, propanol, butanone, benzaldehyde, benzene
Floor wax	Nonane, decane, undecane, dimethyloctane, trimethylcyclohexane, ethylmethylbenzene
Wood stain	Nonane, decane, undecane, methyloctane, dimethylnonane, trimethylbenzene
Latex paint	2-Propanol, butanone, ethylbenzene, propylbenzene, 1,1'-oxybisbutane, butylpropionate, toluene
Furniture polish	Trimethylpentane, dimethylhexane, triethylhexane, trimethylheptane, ethylbenzene, limonene
Polyurethane floor finish	Nonane, decane, undecane, butanone, ethylbenzene, dimethylbenzene

Source: Godish, T., *Indoor Air Pollution Control*, Lewis Publishers, Chelsea, Michigan, 1989.
Tichenor, B.A.,"Organic Emission Measurements Via Small Chamber Testing," in *Proceedings of the Fourth International Conference on Indoor Air Quality and Climate*, pp. 8-15.

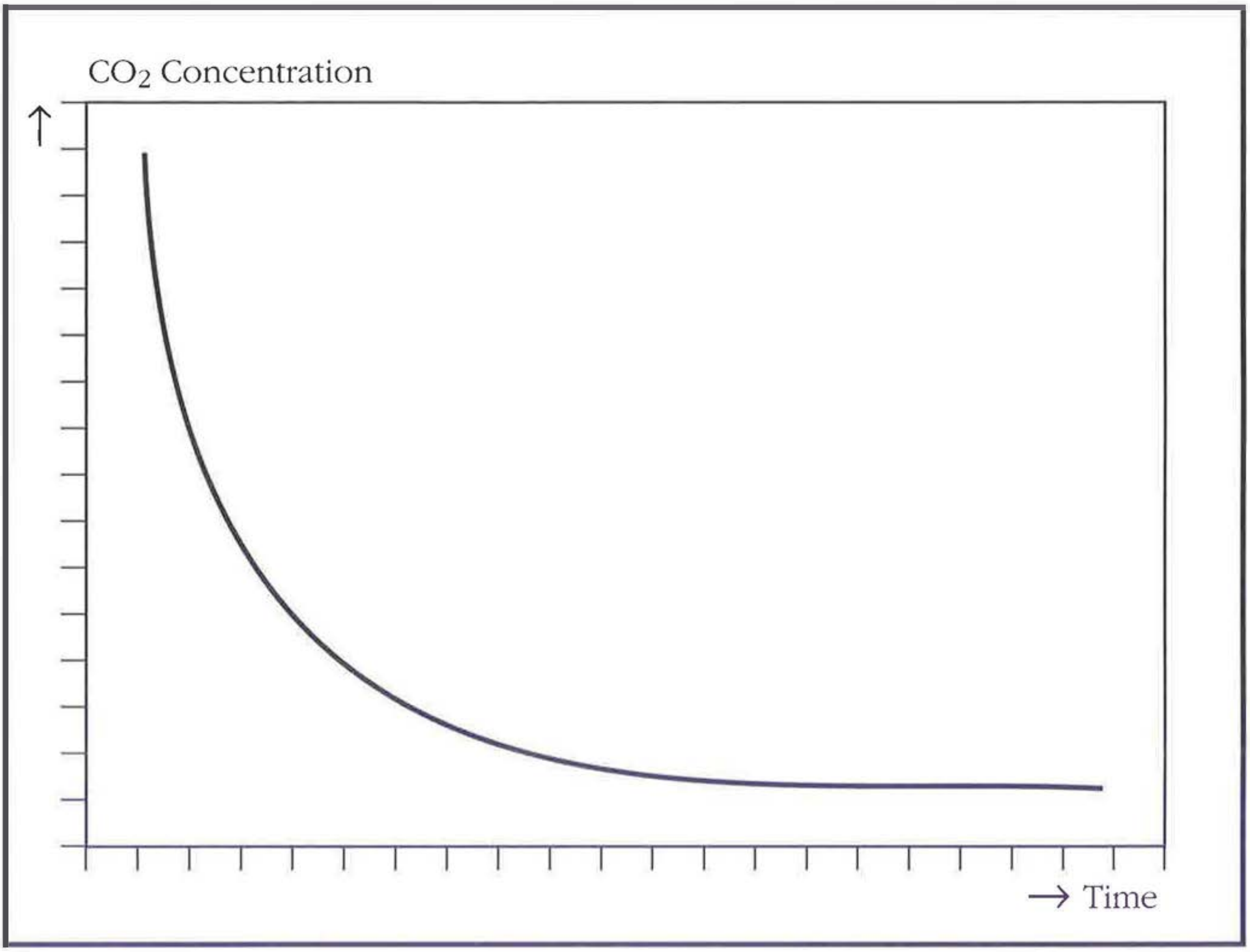
4.4 Purpose of Enhanced Ventilation

Measurements of volatile organic compounds taken after paints or sealers have been applied indicate a very high initial concentration of these compounds, followed by an exponential type of decay of their emission rate. Consequently, it would be beneficial to the comfort and well-being of the occupants if a suitable amount of additional outdoor air could be used to purge the premises following renovations. If the ventilation air is admitted at a higher rate than normal, the acceptable quality of the indoor air will be established more quickly. However, if the ventilation rate cannot be adjusted to run at a higher level, the only option is to run the ventilation system continuously, or for a longer period of time each day.

The enhanced rate of air exchange could be beneficial in at least the following ways:

a) If the space is to be occupied immediately after the new material has been applied, enhanced ventilation may be essential to provide acceptable air quality in the space, until the off-gassing reaches normal rates.
b) If the space can be left vacant for a specified time after the application of the new material, enhanced ventilation would keep the concentration of the undesirable species of chemicals at a lower level. This would reduce the degree of absorption by other materials in the space, for subsequent secondary off-gassing.

OFF-GASSING DECAY IN VENTILATED SPACE



It is a good practice to ventilate as much as possible while the products that are being applied are still wet. This practice minimizes the creation of secondary sources that emit previously absorbed contaminants.

4.5 Duration of Enhanced Ventilation

Enhanced ventilation should be continued until the air quality is acceptable, at which time the ventilation rate is returned to the normal setting. Acceptable IAQ is achieved when the comfort level of contaminant concentration is maintained. If the comfort level concentration is not published, it is safe to assume that a fraction of the TLV (threshold limit value) concentration listed in health protection standards could be used, after consultation with a health authority. ASHRAE recommends the fraction to be between one-half and one-tenth of the TLV.

Enhanced ventilation should not be continued indefinitely because it can be very wasteful of energy. Energy is usually expended in conditioning the incoming air, except at times of the year when weather conditions are such that no humidification/dehumidification or heating/cooling of the outdoor air is required. During these periods, the use of enhanced ventilation could be prolonged, since the only additional cost would be to move the increased air flow.

When outdoor air needs to be conditioned before being admitted, it would be in the best interests of responsible energy management to reduce the ventilation rate to the normal operating level as soon as possible after addition of the new materials. To determine when this should be done, the quality of the air in the space in question should be tested regularly. Based on these tests, a simple mathematical extrapolation comprising the following steps will assist in projecting how much longer the enhanced rate would be required:

1. Initialize time and concentration
2. Evaluate decay constant
3. Project to target concentration
4. Re-initiate projection

This procedure is outlined in Appendix F.

Note: The VENT computer program is useful in calculating the duration of enhanced ventilation.

4.6 Conclusion

Normal ventilation rates, specified by ASHRAE Standard 62-1989, are intended to control IAQ in buildings with no new materials recently installed or added. Where new materials are being installed or added, IAQ must be controlled by an enhanced ventilation strategy that must remain in effect until the off-gassing process decays to a point where the normal ventilation strategy can resume.

5.0 VENTILATION DEMAND CONTROLLER

This section includes a discussion on the ventilation demand controller (VDC), which is a tool that assures adequate ventilation in an office space. With a properly adjusted VDC, ventilation requirements can be met in an energy efficient manner.

The VDC device adjusts the position of outdoor air dampers to match the rate of outdoor air per person with the known rate of carbon dioxide (CO_2) each person generates. This is done by a sensor placed in the return air stream that measures CO_2 concentration in the space, and by a controller that compares the measured information with the predicted concentration, and sends a signal to the damper actuator when required. (See Figure 3.)

As previously discussed, CO_2 concentrations can be used as an indicator of ventilation rates. CO_2 is produced by people through their respiratory process, and can therefore be used to gauge the number of people present. Since outdoor air has a relatively constant concentration of CO_2, and since people working at a given task produce CO_2 at a relatively uniform rate, the relationship between the ventilation rate and the number of people may be developed quite simply. The discussions that follow give details on several possible control strategies that may be used to ensure quantitative adherence to ventilation requirements.

5.1 Steady State Conditions

In office buildings, the concentration of CO_2 normally reaches steady state after a number of hours of operation. Steady state concentration, therefore, is not suitable as a control set-point for a ventilation demand controller. This would result in under-ventilation of the space, while the concentration build-up would be abnormally accelerated until such time when steady state is reached. This strategy would not guarantee compliance with ventilation rate standards in the initial hours of operation.

5.2 Transient Conditions

More commonly, the concentration of CO_2 is not constant in time because it is low at the beginning of the day, then increases toward the steady state, perhaps without ever achieving it. (See Fig. 4). A transient analysis is useful for this period of time. As noted above, the transient condition is the most likely mode of operation.

For control purposes, it is more convenient to think in terms of a maximum or steady state concentration (C_{ss}), toward which the concentration in the space is tending, without having the number of people in the equation explicitly. For this steady state case,

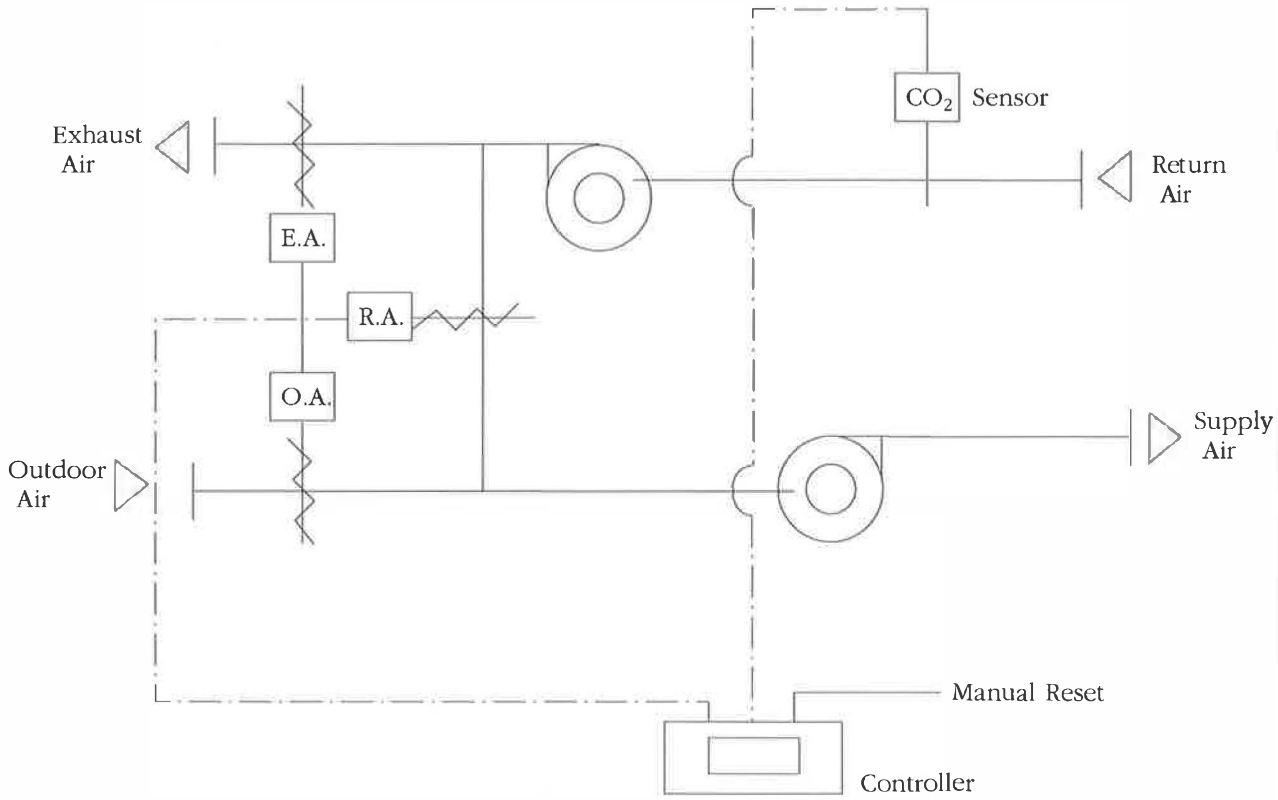
$$C_{ss} - C_{sp} = (C_{ss} - C_{oa}) \exp(-V_r \tau/Vol) \qquad (5\text{-}1)$$

where:

C - concentration of carbon dioxide, (in ppm) with various subscripts as follows:

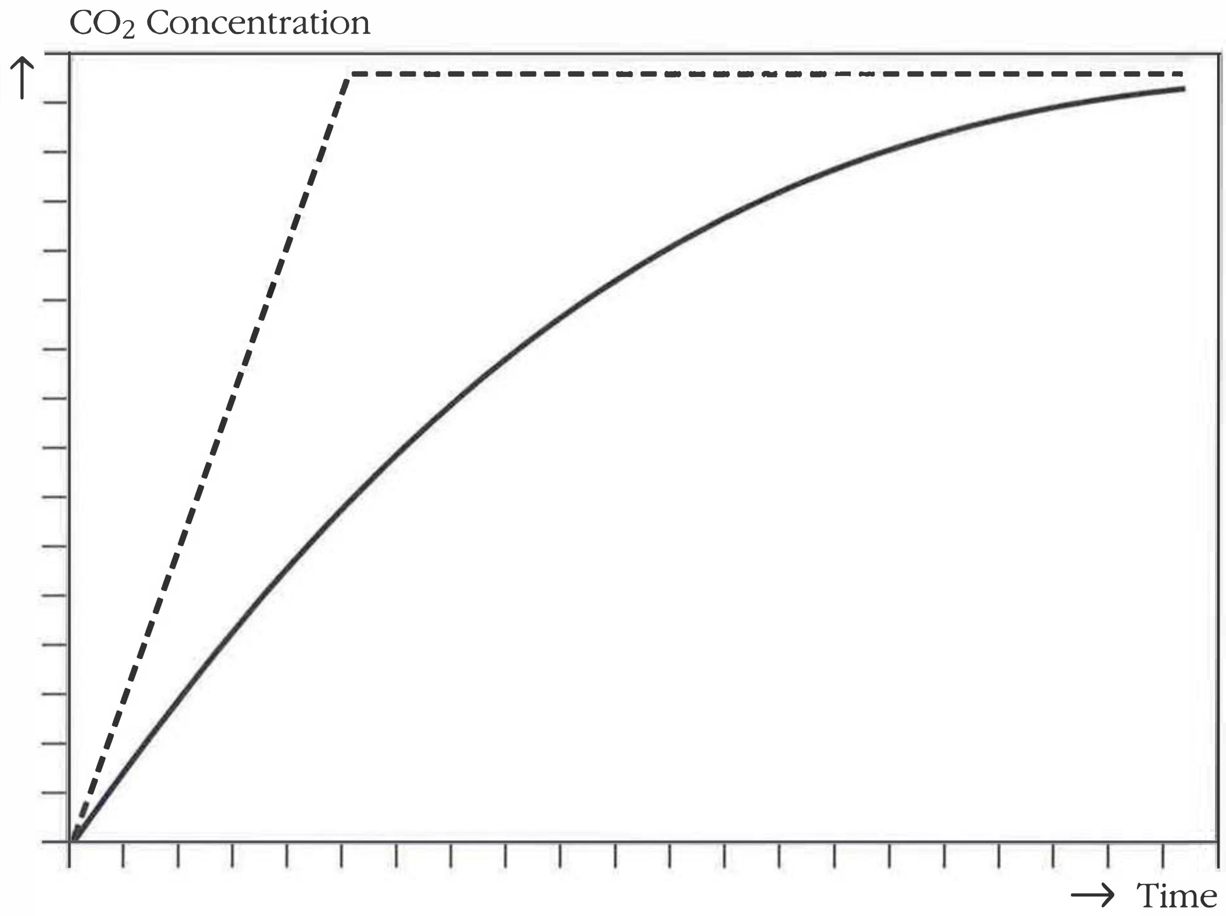
- C_{oa} - denotes the CO_2 in the outside air entering;
- C_{sp} - denotes the concentration in the space;
- C_{ss} - denotes the steady state concentration in the space of interest;
- τ - denotes time;

CONTROL SCHEMATIC FOR VENTILATION DEMAND CONTROLLER



RECOMMENDED CONTROL STRATEGY

Steady State Concentration



- - - Ventilation turned on when CO_2 concentration reaches set point — not recommended for control of IAQ

——— Ventilation on when people enter building — recommended strategy for Ventilation Demand Controller

Vol - denotes the volume of the space under consideration;

V_r - denotes the volumetric flow rate of ventilation air. (This rate applies to both the inlet and outlet, as a steady state is assumed with respect to the overall amount of air in the space.)

By monitoring the concentration change of carbon dioxide in the space, and comparing the trends with the trend given by equation (5-1), it is possible to provide the necessary outdoor ventilation air. The following describes how this is accomplished by using this comparison to set the position of dampers which control outdoor air intake.

5.3 Control Loop

Equation (5-1) is converted into a control algorithm that, for a given building, calculates the transient concentrations of CO_2 to be used for the calculated set point. Based on this, the control loop consists of a CO_2 sensor located in the common return air stream, which measures the actual concentration and the change of concentration over a set interval of time. The controller compares the measured and calculated values and sends a signal to the outdoor air damper operator, which is adjusted as necessary. (See Fig. 3.)

If the measured concentration of CO_2 agrees with the calculated set point, the outdoor air damper setting is correct. If there is a discrepancy between these two values, the control algorithm determines the action to be taken. This involves moving the outdoor air damper until the desired agreement in readings is achieved. A control strategy for this arrangement is described in some detail by Vaculik (see References), who also shows that variations from the simple case depicted by equation (5-1) can be readily accommodated by this control strategy.

5.4 Control Strategy

When contaminants are generated, they mix with the surrounding gases, so that even though there is a purging process going on, the concentrations of the contaminants will build until a steady state is achieved. This steady state concentration is related to the concentration of the outdoor air being admitted, the generation rate of contaminants, and the rate of admission of outdoor air by the relation

$$C_{ss} - C_{oa} = S_r / V_r \qquad (5\text{-}2)$$

Where S_r denotes the source rate of carbon dioxide production.

Clearly, unless the rate of purging is infinite, or the rate of generation is zero, the steady state concentration will be higher than that in the outdoor air being admitted.

The rate of increase of contaminant concentration in the space being purged, before it reaches steady state, may be derived from equation (5-3).

$$C_{ss} - C = (C_{ss} - C_{oa}) \exp(-V_r \cdot \tau / Vol) \qquad (5\text{-}3)$$

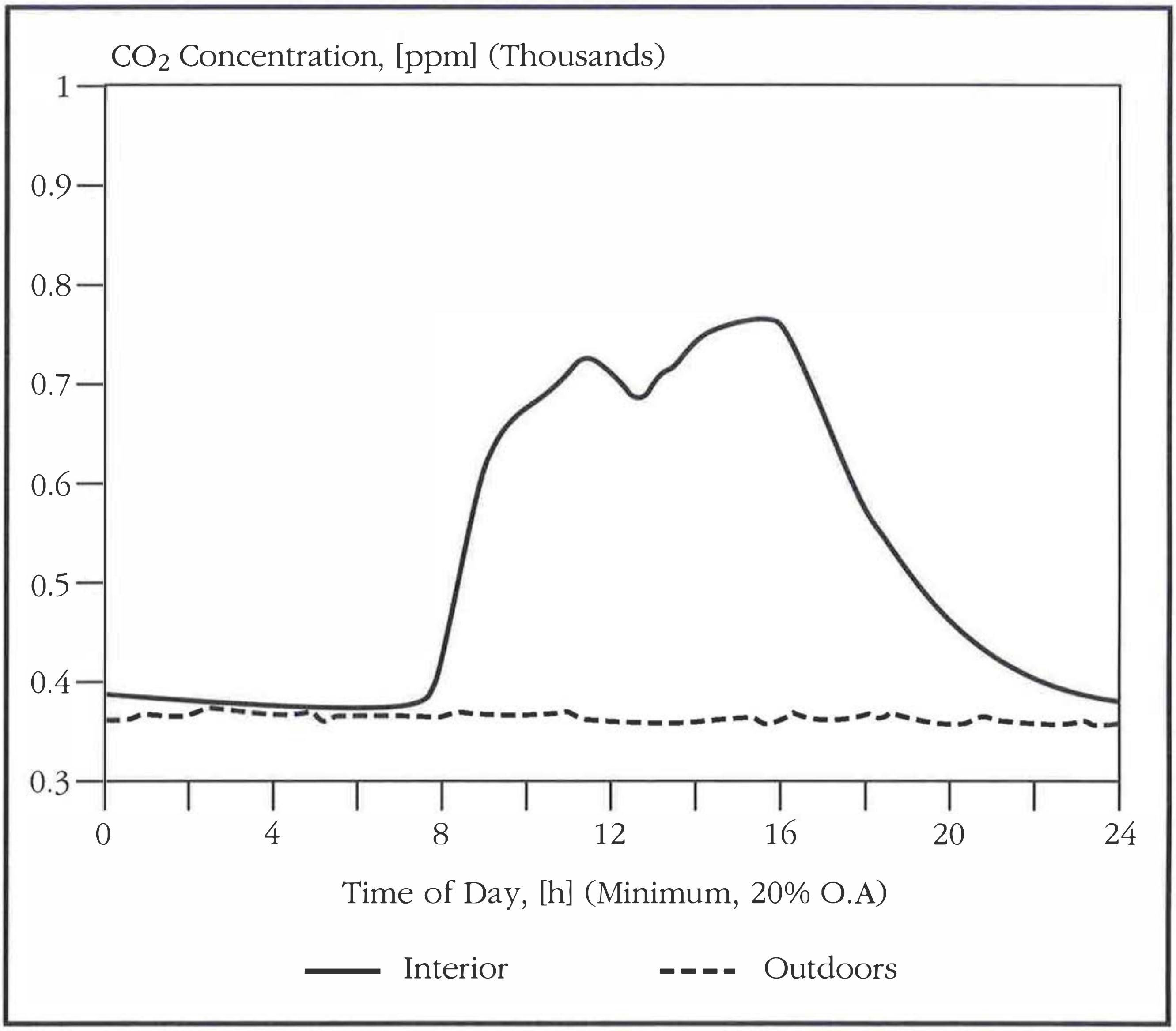
where C is the concentration of the contaminant in volume "Vol" at time "τ", and other terms are as defined following equation (5-1). The form of this relationship is shown in Fig. 4.

The Simplest Model

If all the people, who are the major sources of contaminants, entered the building at the same time, remained in the building for the same length of time, and left at the same time, it would be a simple matter to combine the two expressions, (5-1) and (5-2), to determine the ventilation rate required to avoid exceeding the maximum allowed concentration of contaminant in the office building. Generally, however, this is not the case.

TYPICAL WEEKDAY CO_2 PROFILE IN OFFICE

Thursday, 14 March, 1991: Jeanne Mance Building, National Capital Region



In an office complex in which the occupants are allowed flexible hours, the people do not all enter at the same time, nor do they leave at the same time. Consequently, the source term, S_r, changes with time, so that, unless the ventilation rate changes with it, we observe from equation (5-1) that the steady state concentration would change with time. This is a contradiction in terminology. Similarly, equation (5-2) is developed based on the assumption that C_{SS} is a constant in time, which implies that the source rate is constant in time. In practice, the concept of a steady state concentration being approached may be used, even though, in the strictest mathematical sense, the steady state as defined by equation (5-1) is not really steady because the number of sources changes throughout the day.

In a practical application, the control system may be set up to respond in such a way that the concentrations will asymptotically approach a limit, which will be referred to as the quasi-steady state concentration. This limit can then be chosen somewhat independently of the steady state described above, as long as the air handling system is capable of ensuring that it not be exceeded. Air handling systems with a free cooling option have excess ventilation capacity, so the limit can generally be set to levels which are well within ASHRAE Standard 62-1989.

Deviations from the Simplest Model

The HVAC systems in an office building are generally turned on to provide for some degree of purging with outdoor air prior to occupancy hours, which may bring the CO_2 concentrations down to levels near those in the outdoor air, or at least well below the steady state value experienced during occupancy hours.

Washroom exhaust fans must be in operation whenever the building is occupied. This air is replenished by outdoor air make-up, which forms part of the overall outdoor air introduction for ventilation purposes. When the number of occupants in the building calls for more outdoor air than that exchanged by washroom fans, this washroom exhaust portion would simply form part of the overall outdoor air introduction without affecting the strategy in other ways. If people enter the building over a period of several hours, as is normally the case, washroom exhaust fans would be turned on at the time people begin to arrive. However, an energy efficient strategy for providing additional ventilation air should take over the control system when the number of occupants is greater than the number served by the outdoor air exchanged while washroom exhaust fans are operating.

Considering all the variables, it is possible to conceive of a very large number of concentration-time profiles, each of which is determined by a particular strategy to satisfy the ventilation requirement. Some possible strategies for control of ventilation are discussed in the section below.

As indicated earlier, the simplest model is for the situation in which all occupants enter the building at the same time, stay for the entire day and leave at the same time. If people arrive at the office over an extended period of time, and if some leave at lunchtime and return later, and there is then another distribution of times during which people leave the building at the end of the working day, the concentration of CO_2 will be somewhat lower in the early hours of operation than the concentrations shown in Figure 4.

The concentration, however, should not be lower than that in a building without a VDC, where the minimum outdoor air damper position has been set to comply with the ventilation requirements. In such buildings, the shape of daily concentration of CO_2 resembles the back of a camel, as illustrated in Figure 5.

5.5 Maintenance of the VDC

Carbon Dioxide Sensors

The main maintenance task with these sensors is to check that their calibration has not drifted significantly. This should be done at least every two or three months, by testing their sensitivity to a sample of carbon dioxide. If the calibration is noted to drift excessively, the sensor should be referred back to the supplier for possible replacement.

Since the VDC is active during the mechanical cooling season only, one calibration before and one during the summer should suffice.

Electronic Controller

At the time of installation, the controller will be set up to function appropriately. At this point, the algorithm used to compute the control logic should be verified by a step-through procedure of the control loop. This sequence should be repeated as a regular part of the preventive maintenance program.

When the controller sends an instruction to the motor actuators to change a control setting, it produces an output signal that should also be checked for accuracy. If there appears to be a problem with this signal, the supplier should be consulted.

Motor Actuators and Dampers

The motors used to move the damper positions should be maintained according to the manufacturer's specifications. The dampers should be free from obstruction, and should be lubricated as recommended.

APPENDIX A

A. Project Delivery System

The Project Delivery System is the basic framework within which PWC's real property projects (and those executed by PWC for others) are developed, acquired or implemented, and put into use. The system helps ensure a quality end product, delivered on time and within budget. It can be used to promote and maintain good communications among project team members, including the ventilation engineer.

The PDS has six phases, in which it is recommended that ventilation engineering services be provided as follows.

1. Planning

The product of this phase is an investment plan in response to the tenant/user needs. The ventilation engineering input during this phase is concerned with establishing IAQ criteria, and with the external air pollution in the vicinity of the site that may cause IAQ problems.

2. Definition

The product of this phase is the Project Brief or the Leasing Documentation Package. In either case, ventilation engineering ensures that air handling systems are capable of controlling off-gassing, and that they comply with normal ventilation requirements.

3. Implementation

This phase has two products, a set of construction drawings and specifications, and a built work. The built work is either a base building or a fit-up. In the case of a lease, the base building is usually already built. The ventilation engineering input is limited to the verification of the ventilation requirements defined in the Project Brief, through reviews of construction documentation.

4. Commissioning

The product of this phase is a functioning facility. The most intensive ventilation engineering input is needed during this phase. Enhanced ventilation strategies must be established and implemented first—an especially demanding task on projects with phased occupancy. As the off-gassing process stabilizes, a normal ventilation strategy must be implemented. During this phase, the ventilation engineer must also ensure that the actual volume of outdoor air introduced into each ventilation system meets the ventilation requirements, and that the air distribution to individual work stations is well balanced. See Appendix C for procedures of delivery of enhanced ventilation.

5. Operating

The product of this phase is a facility-in-service that meets the needs of the tenant/user. Ventilation engineering input can be divided into two distinct stages: a relatively intensive stage that takes place during the first year of operation and a second, more routine stage that continues throughout the remaining service life of the facility. Ventilation engineering services are provided either to respond to IAQ complaints, or support to project managers when new fit-up or renovation projects are initiated in response to changing tenant needs.

During the first year of operation, the ventilation engineering services basically include fine-tuning of ventilation rates, adjusting air circulation, and implementation of local ventilation systems. During the remainder of the service life, the ventilation engineering services also include implementation of enhanced ventilation regimes whenever new materials are imported into the building.

6. Evaluation

The aim of this phase is to determine how well the finished facility fulfils the design intent recorded in the Project Brief. The evaluation report helps owners and project leaders determine which design features work and which do not. The ventilation engineering input at this stage consists of exchanging information about experiences and lessons learned.

APPENDIX B

B. Delivery of Normal Ventilation

1. Information Gathering

The ventilation engineer must be familiar with the building, its systems, its surroundings, and any concerns occupants may have about their environment. The most important aspect of the familiarization process is listening to the IAQ-related experiences of the PM and building operators.

Guidelines given in the Level I Manual "Managing Indoor Air Quality" should be followed.

2. Walk-through Inspection

Based on the information gathered in the previous step, a walk-through inspection must be conducted. This will provide additional information about the building and its environment. During this inspection, all potential sources of air contamination should be identified, such as:

- combustion devices;
- copying machines;
- stored chemicals or cleaning supplies;
- open drains;
- HVAC equipment.

During the walk-through inspection, temperatures, relative humidity, CO_2 concentration, and the degree of thermal comfort should be measured at several locations, especially in the work station from which the complaint originated.

3. Initial Review

The purpose of this task is to review and analyze all information obtained to determine:

a) whether any of the systems require cleaning;
b) whether minor adjustments or repair/replacement of faulty components may solve the problem;
c) whether medical experts should be consulted;
d) whether a more detailed assessment of the HVAC system is required.

In most cases, causes of IAQ-related complaints can be discovered at this point. If a more detailed assessment is required, further testing should be done as follows.

4. Detailed Measurements of Temperature, Relative Humidity and CO_2 Concentrations

While spot measurements of these quantities are recommended during the walk-through inspection, more comprehensive testing should be done during this phase. The following equipment and procedure are suggested:

Equipment:
- thermometer;
- relative humidity meter (e.g. Vaisala HMI 31); and
- portable CO_2 detector (e.g. Fuji ZFP 5 or Horiba APBA 210).

Test Procedure:
- select two or three densely occupied floors, including the floor(s) on which a problem has been reported;
- select at least two locations on each floor, and measure the air temperature, relative humidity and CO_2 concentration continually or at hourly intervals throughout the day.

Note: Ventilation engineering services described in Steps 5 through 8 are usually provided by highly specialized personnel.

5. Measurement of Air Change Rates, Air Distribution Pattern, and Contaminant Dispersion Pattern

In buildings with a functioning ventilation demand controller, the following measurements may not be needed, since the VDC calculates the air change rates automatically on a real time basis, providing the VDC is calibrated.

Minimum Air Change Rate

A building's minimum air change rate can be determined by conducting four or five tracer gas decay tests under warm weather and calm wind conditions (i.e. outdoor air temperature above 15° C, and wind speed of less than 20 km/hr), with the outdoor air dampers set at their minimum positions. Appendix G contains a detailed description of the gas decay test.

Air Distribution Pattern

The air distribution pattern can be determined by injecting the tracer gas directly into the supply air flow, then measuring its distribution over time throughout the area served by that system. This method would be more easily quantifiable, in terms of flow distribution, than the first method suggested. This approach is outlined in Appendix H.

Contaminant Dispersion Pattern

The test procedure outlined in Appendix H can be used, except that the tracer gas is injected at one location within a zone (e.g. in one room). Similarly, contaminant dispersion rates can be evaluated, approximately, by injecting a small amount of tracer gas at one location within a zone, and measuring the tracer gas concentrations at regular time intervals both at the injection location and at several other locations on the floor. The faster the concentrations at all the various measurement points approach the same values, the higher the dispersion rate. This technique can be used to evaluate room-to-room dispersion rates.

In general, for areas with known contaminant sources, such as a room with a blueprint machine, the air dispersion rate should be as low as possible to prevent the contaminated air from exhausting to surrounding rooms. For general office areas, on the other hand, the dispersion rate should be as high as possible to facilitate a uniform distribution of outdoor ventilation air.

Contaminant Re-Entry

Tracer gas injection can also be used to determine whether exhaust air re-enters the building. A small amount of tracer gas is injected into an exhaust system, then concentrations are measured at the outdoor air intake of each HVAC system. If tracer gas is detected, the exhaust system's inlet or outlet may have to be relocated. This test should be done under various wind conditions.

6. Identification and Measurement of Contaminants

The objective of this task is to identify the major contaminants in a building, their sources, and their levels of concentration. This can be achieved by analyzing air and water samples collected from several locations inside and outside, particularly inside various compartments of the HVAC systems. Some of these measurements may need to be repeated in other seasons to detect seasonal pollutants.

7. Interim Review

The next step is to identify contaminants whose concentrations must be maintained below certain levels recommended by prevailing standards.

8. Establish Relationship Between Contaminant Concentrations and Air Change Rates

Once these contaminants have been identified, the next step is to either remove the source(s) or to determine how much outdoor air is required to keep contaminant levels below prescribed limits.

To determine the relationship between concentration and air change rate for each contaminant, measure both the concentration and the actual air change rate continuously for one week, then repeat this procedure with four different outdoor air supply rates. For this series of tests, the normal operating schedule of the HVAC systems should not be changed, except that Saturday is treated as a weekday to determine the effect of occupants on the contaminant level. A minimum period of one week of monitoring at each air change rate is suggested, since some sources (such as those associated with cleaning) may have a weekly cycle. This task is beyond the scope of this document.

9. Design and Implementation of Ventilation Solution

See Appendix A, Phase 3.

10. Commissioning

See Appendix A, Phase 4.

11. Monitoring of Compliance with Ventilation Requirement

See Appendix A, Phase 5.

12. Final Review and Report

The final task is to review all test results and obtain any missing information. Follow-up measurements of selected contaminants can also be carried out if adjustments have been made to the HVAC systems, or if potential contamination sources have been removed.

A summary report should be prepared, with results interpreted and presented in a manner easily understood by non-technical persons. The report should include:

- a brief description of the building;
- the nature of the occupants' complaints;
- the actions taken;
- the measurements used; and
- the basis for any recommended remedial measures.

APPENDIX C

C. The Critical Work Station Concept

In office buildings, air distribution systems are generally designed to meet thermal load requirements, and are therefore not linearly related to the distribution of personnel in the office space.

Consequently, the amount of outdoor air in the air distribution system must be high enough to ensure that the work station that receives the least amount of supply air in proportion to its occupancy levels (the critical work station) receives the prescribed minimum rate of outdoor air.

All other work stations will then be "over-ventilated," according to the prescribed ventilation rate. The degree of over-ventilation depends on the diversity of heating and cooling loads in the ventilation zone, and the type and number of air handling units in use.

When most work stations receive more than the prescribed amount of outdoor air, the total return air will have a lower concentration of contaminants than the return air from the critical work station. Since the total return air has not been contaminated to the allowable limit, that portion of it which is mixed with the incoming outdoor air in the mixing chamber is still capable of removing air contaminants from the office space. This reduces the conditioning of the outdoor air, thereby reducing energy consumption.

Equation (6-1) of the ASHRAE Standard 62-1989, shown below as equation (C-1), is used to compute the required outdoor air flow rate for a ventilation zone.

In each ventilation zone, which is a portion of a building serviced by one ventilation make-up air unit, there is at least one critical work station which receives relatively the lowest rate of supply air per person. Such a work station is located in what is termed below as "critical space."

$$\dot{V}_{ot} / \dot{V}_{st} = \{\dot{V}_{on} / \dot{V}_{st}\}/\{1. + \dot{V}_{on} / \dot{V}_{st} - \dot{V}_{oc} / \dot{V}_{sc}\} \qquad \text{(C-1)}$$

where:

$\dot{V}_{ot}/\dot{V}_{st}$ = Corrected fraction of outdoor air in system supply

$\dot{V}_{on}/\dot{V}_{st}$ = Uncorrected fraction of outdoor air in system supply

$\dot{V}_{oc}/\dot{V}_{sc}$ = Fraction of outdoor air in critical space

$\dot{V}_{ot}$ = Corrected total outdoor air flow rate

$\dot{V}_{st}$ = Total supply flow rate, i.e. sum of supply flow rates for all branches on system

$\dot{V}_{on}$ = Sum of outdoor air flow rates for all branches on system

$\dot{V}_{oc}$ = Outdoor air flow rate required in critical branch

$\dot{V}_{sc}$ = Supply flow rate in critical branch

The procedure for using equation (C-1) is as follows:

1. Compute the uncorrected outdoor air fraction by dividing the sum of all the branch outdoor air requirements by the sum of all the branch supply flow rates.

2. Compute the critical zone outdoor air fraction by dividing the critical zone outdoor air requirement by the supply flow rate.

3. Evaluate equation (C-1) to find the corrected fraction of outdoor air to be provided in the system supply.

APPENDIX D

D. Indoor Air Quality Procedure

The indoor air quality procedure makes it much easier to verify compliance with the ASHRAE Ventilation Standard, or lack of it, than does the ventilation rate procedure described in Subsection 3.5. Instruments are commercially available for this test which allow the necessary measurements to be taken while the operator is far enough away to avoid distorting the readings.

With this method, a sensor is placed in a suitable location to detect the CO_2 concentration. The sensor should be placed in the office to be checked, at a location which will give a representative concentration of the CO_2 level. It should be placed so that it does not directly pick up the gases exhaled by the office occupant, since this would not be representative of the concentration in the space. If possible, place the sensor in the return air intake, immediately in the flow path of the return air.

Measured CO_2 data need to be converted into the ventilation rate, expressed in litres of outdoor air per second per person. The following is a detailed description of this conversion.

The above figure represents the volume to be ventilated. The space has air entering and leaving, and has a contaminant source within it. A number of possibilities exist for the space within the box, such as:

1. It may be at a steady state concentration, so that carbon dioxide is being depleted (by the flow of outdoor air into the space) at the same rate it is being produced by the source.

2. The CO_2 concentration may fluctuate. Concentrations will increase with time if the source produces more CO_2 than the ventilation air removes, and decrease if the situation is reversed. In this case, it may be that there is a source of CO_2 with no ventilation air moving, or that the ventilation air is flowing and there is no source of CO_2.

Having a control system within a ventilation system to produce steady state CO_2 at all times would be difficult and impractical. It should be noted, however, that the ventilation rate may be a steady flow so that the rate of incoming air equals the rate of air leaving. This would result in overall mass steadiness, even though the contaminant concentrations change with time. Therefore, the case with steady flow with a non-steady concentration is the most common.

In the examples that follow, the reference to steady or non-steady will refer to the carbon dioxide concentrations only, since it is assumed that whenever the ventilation system is in operation, the flow into the space will equal the flow out of it.

Since the steady (concentration) case represents the cross-over between an increasing and a decreasing concentration when the ventilation is in operation at the same time as a source is present, it is of some interest to evaluate. It will be considered first, followed by the general cases with changing concentration.

Steady State Concentration

Since it is assumed that the overall mass of "air" in the space is constant, the conservation of carbon dioxide relationship implicitly states that whatever is not carbon dioxide is "other air."

The rate of CO_2 entering $= C_{in} \cdot V_r$

The rate of CO_2 leaving $= C_{out} \cdot V_r$

The rate of production of CO_2 $= S_r$

(Notation appears at the end of this Appendix.)

Generally, then, if the concentration changes with time, the differential equation describing the conservation of carbon dioxide in the space is:

$$d(C_{sp} \cdot Vol)/d\tau = (C_{in} \cdot V_r) - (C_{out} \cdot V_r) + S_r \quad \text{(D-1)}$$

For the case of steady state carbon dioxide concentration, the required ventilation rate is: (since $d(\ )/d\tau = 0.$)

$$V_r = S_r /(C_{out} - C_{in}) \quad \text{(D-2)}$$

If the only sources of carbon dioxide in the space are the people, all of whom are functioning with the same respiration rate, then:

$$S_r = N \cdot RR \cdot C_{rr} \quad \text{(D-3)}$$

If people are operating at different respiration rates, or if other sources of carbon dioxide production exist, this last equation would be a summation over all the sources.

Example:

If C_{out} = 800 ppm

C_{in} = 350 ppm

RR = 8 litres/min/person (as for light office work)

C_{rr} = 38,000 ppm CO_2

Then:

S_r = 0.304 (litres CO_2/min/person)

= 0.005 (litres CO_2/sec/person)

and the resulting ventilation rate to maintain steady state is:

V_r = 11.25 litres/sec/person

Therefore, a ventilation flow rate of 11.25 litres/sec/person would be required to maintain steady state at the conditions used in the example.

Transient Conditions, With or Without Generation

As noted earlier, the transient condition is the most likely mode of operation. For this condition, the rate at which concentration levels change is important. The differential equation must be solved for this case. Upon rewriting it, we note that C_{sp} is the concentration in the space, which is also assumed to be the concentration of the air leaving the space, C_{out}. The ventilation rate will be assumed constant for solution of equation (D-1).

$$d(C_{sp} \cdot Vol)/d\tau = (C_{in} \cdot V_r) - (C_{out} \cdot V_r) + S_r \quad \text{(D-1)}$$

Since C_{in} is assumed constant in time, and $C_{out} = C_{sp}$, as noted above, equation (D-1) may be rewritten as:

$$d(C_{sp} - C_{in})/d\tau = - (C_{sp} - C_{in})(V_r/Vol) + S_r/Vol \quad \text{(D-4)}$$

In this case, V_r is constant, but S_r may vary with time if the number of people in the space varies with time. The general solution to this differential equation, for V_r constant, is of the form:

$$C_{sp} - C_{in} = \exp(-V_r \cdot \tau/Vol)\{\int(S_r/Vol) \cdot \exp(V_r \cdot \tau/Vol)d\tau + C_i\} \quad \text{(D-5)}$$

where C_i is a constant of integration to be evaluated at time $\tau = 0$. If the number of sources changes with time, the general solution would depend on this function of time. If S_r is constant with time, the general solution may be written as:

$$C_{sp} - C_{in} = S_r/V_r + C_i \cdot \exp(-V_r \cdot \tau/Vol) \quad \text{(D-6)}$$

finally, if $C_{sp} = C_o$ when $\tau = 0.$, then the solution is:

$$C_{sp} - C_{in} = (S_r/V_r) \cdot \{1 - \exp(-V_r \cdot \tau/Vol)\} + (C_o - C_{in}) \cdot \exp(-V_r \cdot \tau/Vol) \quad \text{(D-7)}$$

Some special cases of this expression will be considered next.

Carbon Dioxide Source with No Ventilation

When the ventilation rate is set to zero, the source term on the right side of equation (D-7) becomes indeterminate, since both the numerator and denominator go to zero. L'Hopital's rule allows the limiting function to be obtained, which may be written as follows:

$$C_{sp} - C_{in} = S_r \cdot (\tau/Vol) + (C_o - C_{in}) \qquad (D\text{-}8)$$

or, since C_{in} is meaningless, when no flow is entering,

$$C_{sp} = S_r \cdot (\tau/Vol) + C_o \qquad (D\text{-}9)$$

This form of equation may be obtained more easily by setting up the original differential equation without any ventilation flow included. It clearly shows the expected increase of concentration of carbon dioxide with time.

No Carbon Dioxide Source, with Ventilation

This case may be readily obtained from equation (D-7) by setting the source term to zero, resulting in:

$$C_{sp} - C_{in} = (C_o - C_{in}) \cdot \exp(-V_r \cdot \tau/Vol) \qquad (D\text{-}10)$$

This equation (D-10) applies to the decrease of CO_2 concentrations with time, when the ventilation system is operating but no people are present to contribute to the CO_2 levels. This equation could then be used to interpret data taken after working hours, provided there are no people present. If a person is needed to take the data, strictly speaking, this equation will not apply.

Equation (D-10) can be arranged to solve for the ventilation rate as follows:

$$V_r/Vol = (1/\tau) \cdot \ln\{(C_o - C_{in})/(C_{sp} - C_{in})\} \qquad (D\text{-}11)$$

This equation can be used to compute the rate of air changes in the space, given the concentration change with time, and the concentration of the incoming fresh air. This can be used to compute the ventilation rate if the volume is specified and no sources are present.

Some Carbon Dioxide Source with Ventilation

Equation (D-11), as noted, applies only when no sources of carbon dioxide are present. Since most meters used to measure CO_2 must be read by a human observer, this means a source of carbon dioxide is present. It is, therefore, of interest to evaluate the effect that the presence of one or two people may have, to investigate the validity of the use of equation (D-11) in such a case.

The general relation (equation D-11) which relates the concentrations to the generation and ventilation rates may be rearranged as follows:

$$V_r = (Vol/\tau) \cdot \{\ln(C_o - C_{in} - S_r/V_r) - \ln(C_{sp} - C_{in} - S_r/V_r)\} \qquad (D\text{-}12)$$

When the source, S_r, is zero, this equation reverts to being identical with equation (D-11). When S_r is non-zero, it permits the actual ventilation rate to be computed when a source, such as a person reading the meter, is present in the space. Although it is clear that equation (D-12) is not as directly solvable as equation (D-11) since V_r appears on both sides of the equation, it can be readily solved by an iterative technique.

Application of Theory to Obtain Ventilation Rate

The theory developed in this section suggests several ways of determining the ventilation rate based on measured values of the carbon dioxide concentration. The simplest of these is the decay method, which is used when no carbon dioxide sources are present and the ventilation system is on at a steady rate during the measurement time period. Equations (D-10) and (D-11) are applicable to this case.

To apply these, it is necessary to obtain measurements of CO_2 concentration for at least two consecutive times, separated by a time interval "τ". Applying equation (D-11) then allows the current ventilation rate to be evaluated.

Example:

At time 17:00, the CO_2 concentration was 650 ppm.
At time 17:25, the CO_2 concentration was 575 ppm.
The outdoor air had a CO_2 concentration of 350 ppm.
Volume of the room under consideration: 50 cu. metres

Applying equation (D-11) gives the following result:

$$V_r/Vol = (1/25 \text{ min}) \cdot \ln\{(650 - 350)/(575 - 350)\}$$

$$= 0.0115 \text{ min}^{-1} = 0.69 \text{ hr}^{-1}$$

For a volume of 50 m^3, this corresponds to 34.5 m^3/hr of outside ventilation air, or 9.6 L/s of outdoor air entering.

More than one set of readings should be taken, since the reading accuracy is not always 100 percent. By taking readings over a period of several hours (if everything is operating in steady state) and plotting the results, a best fit line through the points will, to some extent, overcome some of the inaccuracies in readings.

If these measurements were taken with one or more persons in the space, then equation (D-12) should be used, with an appropriate estimate of the source term. An iterative solution will be required in that case.

Notation

- C - concentration of carbon dioxide, (in ppm) with various subscripts as follows:
- C_{in} - denotes the concentration of carbon dioxide in the air entering as outdoor air;
- C_{out} - denotes the concentration of carbon dioxide in the air leaving the space, which is assumed to be the same as the average concentration within the space (equals C_{sp});
- C_{rr} - denotes the concentration of carbon dioxide in the respiration air emitted by people in the space;
- C_{sp} - denotes the concentration in the space;
- C_{ss} - denotes the steady state concentration in the space of interest;
- N - denotes the number of people in the space who are contributing to the generation of carbon dioxide;
- RR - denotes the respiration rate of people occupying the space;
- S_r - denotes the source rate of carbon dioxide production;
- τ - denotes time;
- Vol - denotes the volume of the space under consideration;
- V_r - denotes the volumetric flow rate of ventilation air. (This rate applies to both the inlet and outlet, as a steady state is assumed with respect to the overall amount of air in the space.)

APPENDIX E

E. Delivery of Enhanced Ventilation

When new materials are scheduled for installation, enhanced ventilation should be considered to avoid IAQ complaints. Where enhanced ventilation is not implemented, experience shows that complaints escalate to a point that the building may be labelled a "sick building" — a label which is very difficult to eradicate. The following steps are recommended:

1. Identification of Source

The manufacturer or supplier of the material to be installed may know what the predominant air contaminant is, to be used as an indicator of off-gassing process control. The off-gassing rate per unit of that material may also be known. If this information is not available, laboratory tests may be required.

2. Definition of Ventilation Requirements

Enhanced ventilation requirements are determined, based on the information obtained in the previous step, on the estimate of the amount of material to be installed, and on the surface area from which it will off-gas. These will vary according to:

- the availability of heating or cooling capacity for enhanced ventilation rates;
- outdoor temperature;
- the type of air handling system;
- the energy management policy;
- the time allowed for off-gassing; and
- other factors that may affect the design of enhanced ventilation strategy.

3. Design and Implementation of Ventilation Solution

Where a satisfactory solution to off-gassing control cannot be achieved through modifications to ventilation strategy, perhaps an interim solution could be used, such as exhausting the off-gassing space directly to the outdoors, either through a window or a dedicated shaft.

4. Monitoring

The monitoring procedures are thoroughly described in Appendix F.

5. Change-over to Normal Ventilation Strategy

When the concentration of the predominant air contaminant reaches an acceptable level, the enhanced ventilation cycle is over and normal ventilation can resume. Methods of assuring compliance with ventilation requirements are presented in Section 3 of this document.

APPENDIX F

F. Determining and Monitoring Enhanced Ventilation

It is generally accepted that the rate of off-gassing may be represented by an exponential function. Measured quantities are needed to set the constants for the exponential, since the exponential decay depends on a variety of parameters which cannot easily be evaluated for a given case. Further research may prove that the actual decay may be most accurately represented by a compound exponential to represent the various mechanisms involved. However, for the purposes of ventilation engineering, let us suppose that it can be represented by a simple function, to a first order approximation, such that the concentration of the contaminant in the space is given by:

$$C = C_o \exp(-\alpha(\tau - \tau_o)) \quad \text{(F-1)}$$

where C_o is the concentration at the first measurement time when $\tau = \tau_o$; α is the decay constant. The procedure for using this to project the time required may be sequenced as follows:

1. Initialize Time and Concentration

Make an initial measurement of the concentration of the contaminant that is to be reduced. Denote this concentration as C_o. Note the time. Subsequent time will be relative to this time, τ_o.

2. Evaluate Decay Constant

After a time interval, at $\tau = \tau_1$, the concentration is measured to be C_1. Using the values of the concentration measured at these two times now allows the decay constant "α" to be evaluated. That is:

$$\alpha = \ln(C_o/C_1)/(\tau_1 - \tau_o) \quad \text{(F-2)}$$

3. Project to Target Concentration

The information obtained to this point in the procedure may now be used to estimate the time at which the concentration is reduced to another, lower value. Suppose the lower concentration desired is denoted as C_f. The projected time to achieve C_f is obtained when $\tau = \tau_f$, which is:

$$\tau_f = \tau_o + \ln(C_o/C_f)/\alpha \quad \text{(F-3)}$$

Since the actual decay will not be a simple exponential as used in these equations, it would be advisable to update the estimates from time to time. This would be done by returning to Step 1, setting new values for C_o and τ_o, and following the procedure through Steps 2 and 3. This sequence can be followed until the concentration has been reduced to the desired level. This projection is useful because it gives at least an approximate indication of how long it will take.

Example Problem

As an example of the type of calculation that might be done, consider a case in which the volatile organic compounds had a concentration of 100 mg/m^3 as measured at 12:00 noon, on Monday, December 3. On Wednesday, December 5, also at 12:00 noon, the concentration was measured to be 10 mg/m^3, after ventilating the space continuously in the time between the measurements. If this same procedure was continued, when would it be expected that the concentration would be 0.5 mg/m^3?

1. Initialize Time and Concentration

Since the measurements have been taken, Step 1 is a matter of identifying the variables. In this case they are:

C_o = 100 mg/m^3
τ_o = 12:00 on December 3

2. Evaluation of Decay Constant

Here again, the measurements have been taken and the variables are as follows:

C_1 = 10 mg/m^3
τ_1 = 12:00 on December 5

The time interval ($\tau_1 - \tau_o$) is 48 hours. The first stage of the decay constant is now evaluated to be:

$$\alpha_1 = \ln\{100./10.)/48 \text{ hrs} = 0.04797 \text{ hrs}^{-1}$$

It should be noted that the units for the concentrations cancel because they are the same units. If the measurements were taken in different units, it is essential to have the same units for C_1 and C_o before evaluating the logarithmic term, in order that the result may be interpreted.

3. Project to Target Concentration

In this case, the target concentration for this time estimate is 0.5 mg/m^3. While this may not necessarily be the final target concentration, it is at least an intermediate value that is of interest. We can then solve for the time τ_f, as:

$$\tau_f - \tau_o = \ln\{100./0.5\}/0.04797 \text{ hrs}^{-1}$$
$$= 110.45 \text{ hrs}$$

This suggests that after 110.45 hours from the initial measurement at 12:00 on December 3, the reading may be expected to be 0.5 mg/m^3. That is, just after 2:00 a.m., on Saturday, December 8, the reading may be as low as 0.5 mg/m^3, if the rate of decline continues on the same exponential as is in effect during the first 48-hour period. Since this is unlikely, a reading is taken at 2:00 p.m. on Friday, December 7, and the concentration is found to be 4.5 mg/m^3. Clearly the additional 12 hours will not bring the concentration down to the target of 0.5 mg/m^3, and a new estimate should be made.

4. Re-initiate Projection

For this next estimate, take the value at the previous τ_1 as being the new τ_o, and the reading taken at noon on Friday, December 7, as being the new reading at τ_1. Then,

C_o = 10 mg/m^3
C_1 = 4.5 mg/m^3
($\tau_1 - \tau_o$) = 50 hrs

The second decay constant is now estimated, based on these numbers to be:

$$\alpha_2 = \ln(10./4.5)/50 \text{ hrs} = 0.01597 \text{ hrs}^{-1}$$

Then, the projected time, from this initial condition to reduce the concentration to 0.5 mg/m^3 is:

$$\tau_f - \tau_o = \ln(10./0.5)/0.01597 \text{ hrs}^{-1}$$
$$= 187.58 \text{ hrs}$$

This second estimate is based on zero time being at 12:00 on Wednesday, December 5. In that case, this estimate is that it will take until about 7:30 a.m. on Thursday, December 13 to reach the target concentration, if the decay follows this second rate faithfully. It is unlikely to follow even this rate exactly, so it would be advisable to take another reading, perhaps about three or four days after the last one, and update the estimate.

This type of declining rate is quite typical, and to be expected in any real situation, although the numbers will vary with the application.

APPENDIX G

G. Tracer Gas Method for Determining Ventilation Rate

Information Required

The following information relating to the building should be gathered before testing begins:

- age of the building
- construction type
- number of floors or storeys
- perimeter dimension (m)
- height dimension (m)
- typical floor plan
- building volume (m^3)
- number of occupants

Equipment Required

Each member of the sampling team should have the following items:

- a stopwatch;
- a marking pen capable of writing on Vacutainers;
- 60 Vacutainers (e.g. Fisher 02-683-54);
- two 60 cc hypodermic syringes with Luer-Lok tips;
- two 21G1 hypodermic needles.

Test Conditions

Whenever possible, tests should be conducted under the following conditions:

- outdoor air temperature of at least 15° C;
- calm wind speed;
- outdoor air supply dampers at minimum opening position (in order to test for the minimum air change rate);
- closed exterior windows and doors;
- open interior doors;
- HVAC systems in normal operating mode.

Team

One person per two to three floors.

Test Duration

Four to five hours per test.

Preparation for Test

a) Calculate the internal volume of the test building, V_b (m^3)

b) Calculate the volume of (SF_6) tracer gas required to achieve a set concentration of SF_6 in the building (50 ppb is recommended), using the relation:

$$V_g = V_b \cdot C_t \qquad \text{(G-1)}$$

where: V_g = volume of SF_6 tracer gas at atmospheric pressure,
V_b = building volume,
C_t = concentration of tracer gas when uniform throughout the building, (50 ppb recommended)

Example: A building of volume 80,000 m^3 and a concentration goal of C_t = 50 ppb, requires a volume of SF_6 of:

$$V_g = 80{,}000\ (m^3) \cdot 50\ (ppb) \cdot 10^3\ (L/m^3) \cdot 10^{-9}\ (ppb^{-1})$$
$$= 4\ L \text{ (at atmospheric pressure and ambient temperature)}$$

c) Prepare the required amount of pure SF_6 tracer gas and store in a suitable pressurized container.

d) Determine locations within the building at which to perform the air sampling:

- select 5 to 10 typical floors;
- mark the sampling locations on the floor-plans, including the main return ducts and 4 or 5 locations in the occupied space.

e) Prepare Vacutainers for sampling by taping septums securely in place; (Note: each test will require approximately 400 Vacutainers.)

f) Assemble the items of equipment required by each member of the sampling team, as listed in Equipment Required above.

Test Procedure

a) Record test date and start time.

b) Measure and record:

- outdoor air temperature °C;
- wind speed km/h;
- wind direction;
- indoor air temperature °C.

Note: Weather information can be obtained from a local weather station; if the subject building is in the vicinity of other large buildings, it is quite likely that the wind conditions will be somewhat different from those given by the weather station.

c) Have the sampling team gather at a pre-determined location within the building and zero all stopwatches.

d) Start all stopwatches simultaneously, then disperse the sampling team to the selected sampling positions/floors.

e) Release the tracer gas into the main supply duct of each HVAC system, noting the time when this is done. The amount of tracer gas released at a given location is computed based on the relative floor area served by that system.

Note: Make sure the tracer gas container is tightly sealed, and do not bring it into the building until all is ready for its release.

f) Begin taking samples of air/gas 30 minutes after the tracer gas is released.

g) Use the following procedure for taking gas samples:

1. Just before the scheduled sampling time, purge the 60 ml syringe twice with room air, at the first sampling location;
2. Draw a 60 ml sample of air/gas into the syringe, at the first location;
3. Pause several seconds to permit the gas in the syringe to stabilize to atmospheric pressure, then push the plunger forward to the 50 ml mark;
4. Insert the syringe needle through the septum of a Vacutainer;
5. Without exerting any pressure on the plunger, observe the syringe plunger to be drawn forward to approximately the 30-35 ml mark on the syringe (caused by the initial vacuum in the Vacutainer).

   Note: If the plunger fails to draw near the 30-35 ml mark, discard the Vacutainer, and repeat steps 1 through 5.

6. Push the plunger forward to the end of the syringe to inject the remaining sample into the sampling tube (Vacutainer).
7. While holding the syringe plunger at its most forward position, remove the needle from the tube, and record the sampling time and location.
8. Move to the next assigned sampling location and repeat steps 1 through 8, repeating this procedure at each location until samples have been gathered at each location.
9. Repeat steps 1 through 8 at 15-minute intervals for two hours following release of the tracer gas.

h) At the completion of the SF_6 sampling, once again measure and record:

- outdoor air temperature °C;
- wind speed km/h;
- wind direction;
- indoor air temperature °C.

Data Analysis

A gas chromatograph equipped with an electron capture detector should now be used to analyze the SF_6 concentrations in the sampling tubes. The results should be treated as follows:

a) For each sampling location, plot the logarithm of the SF_6 concentrations against time (in hours).

b) Fit the data with a straight line, for the period of time during which the concentration decreases with time, and obtain the air change rate by calculating the slope of the fitted line, as follows:

Since the tracer gas was released once and there were no further releases of gas during the time of measurement, the change of concentration with time caused by the purging action of the ventilation air, after the tracer has been thoroughly mixed with the surrounding air, is given by the relation:

$$dC/d\tau = -\beta C \qquad \text{(G-2)}$$

where: C is the tracer gas concentration,
$C = C_1$ when $\tau = \tau_1$
τ = time
β = the air change rate = V_r/Vol
V_r = the volumetric flow rate of ventilation air
Vol = the volume of the space under consideration

Equation (G-2) may be integrated to give the result

$$C_\tau = C_1 \exp(-\beta(\tau - \tau_1) = C_1 \exp(-\beta \cdot \Delta \cdot \tau) \qquad \text{(G-3)}$$

When the slope of the plot of logarithm of concentration vs. time is taken, the air change rate is obtained from:

$$\beta = \frac{1}{\Delta \cdot \tau} \ln(C_1/C \cdot \tau) \qquad \text{(G-4)}$$

$$= \{\ln(C_1) - \ln(C \cdot \tau)\}/\Delta \cdot \tau \qquad \text{(G-5)}$$

For the case under consideration, for the method given, it would be expected that the concentration at the various points of measurement would first show an increase with time, while the tracer gas is mixing with the surrounding air, and then would show the decay suggested by this sequence of equations (G-2 to G-5). In this case, only the decaying portion of the variation should be plotted to obtain the air change rate.

c) Calculate the air change rates for all sampling locations and calculate the average air change rate. If the outdoor air dampers were set at their minimum position for these tests, this would represent the minimum air change rate.

d) Calculate the average outdoor air supply rate per person based on the average air change rate.

APPENDIX H

H. Tracer Gas Method for Determining Air Flow Distribution

For this test, gather the same information relating to the building as in Appendix G above.

Equipment Required

Each member of the sampling team would be advised to have the following items:

- a stopwatch;
- a marking pen capable of writing on Vacutainers;
- 50 Vacutainers (e.g. Fisher 02-683-54);
- two 60 cc hypodermic syringes with Luer-Lok tips;
- two 21G1 hypodermic needles.

Test Conditions

These tests should be conducted under the normal operation mode of the building's HVAC systems.

Team

One person per two to three floors.

Test Duration

Four to five hours per test.

Preparation for Test

a) Calculate the internal volume of the test floor served by the HVAC system in question, V_f (m^3).

b) Calculate the volume of (SF_6) tracer gas required to achieve a set concentration of SF_6 on the floor under investigation (50 ppb is recommended), using the relation:

$$V_g = V_f \cdot C_t \qquad \text{(H-1)}$$

where: V_g = volume of SF_6 tracer gas at atmospheric pressure

V_f = volume of the floor under investigation

C_t = concentration of tracer gas when uniform throughout the floor under investigation (50 ppb recommended).

Example: A floor (zone) of volume 1,200 m^3 and a concentration goal of C_t = 50 ppb, requires a volume of SF_6 of:

$$V_g = 1{,}200\ (m^3) \cdot 50\ (ppb) \cdot 10^3\ (L/m^3) \cdot 10^{-9}\ (ppb^{-1})$$

$$= 0.06\ \text{L (at atmospheric pressure and room temperature).}$$

c) Prepare the required amount of pure SF_6 tracer gas and store in a suitable pressurized container.

d) Determine locations within the HVAC zone at which to perform the air sampling, and mark these locations on the floor plan including the main return ducts and 7 or 8 locations in the occupied space.

e) Prepare Vacutainers for sampling by taping septums securely in place. (Note: each test will require approximately 100 Vacutainers.)

f) Assemble the items of equipment required by each member of the sampling team, as listed in Equipment Required above.

Test Procedure

Follow steps a) to e) of the test procedure for determining air change rates (see page 58), but only release the tracer gas into one HVAC system. Then:

f) Begin taking samples of air/gas 10 minutes after the tracer gas is released.

Follow the same steps for taking gas samples as outlined in g) of the previous test procedure (see page 58).

Data Analysis

Follow the same data analysis procedure as outlined in the previous test procedure (see page 59.) For this test, since only one HVAC zone was doped with a tracer gas, the resulting decay indicates the rate at which air changes are taking place in the zone under study. It does not, however, mean that this is the rate of outdoor air displacing the air in the space, since air from a common return which does not contain the tracer gas would have the same diluting effect as the outdoor air.

APPENDIX I

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