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AIR QUALITY CONTROL IN OFFICE BUILDINGS
BY A CO₂ METHOD

by

F. Vaculik, Dipl. Mech. Eng.

A thesis submitted to the Faculty of
Graduate Studies and Research in partial fulfillment
of the requirements for the degree of
Master of Engineering.

Faculty of Engineering
Carleton University
Ottawa, Ontario
April 28, 1987

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ABSTRACT

This thesis proposes a new CO_2 method of indoor air quality control in office buildings. The method is based on a control of concentration of CO_2 which is generated by the occupants at a known rate per person. The measured CO_2 concentration is used as a measure of the outdoor air quantity necessary for the process of purging air contaminants by outdoor air. The outdoor air quantity, in turn, is based on the ASHRAE ventilation standard, and reflected in the occupancy agreements as the measure of indoor air quality.

The method is based on calculation of the control set point required to obtain the desired CO_2 concentration indoors. The calculation is based on a transient state relationship for CO_2 concentration buildup. The calculated set point is proposed to be compared with the measured concentration. A deviation from the calculated set point is proposed to be converted into a signal to adjust the outdoor air damper position.

The thesis presents a series of analyses of all ventilation parameters, on which is based the proposed control strategy. The strategy is expected to comply with the requirements of the ventilation standard during occupied hours, and to purge the building effectively during a purging cycle in the pre-occupied hours. The proposed control strategy is expected to perform the ventilation service in an energy effective manner.

The air quality issue, to be satisfactorily resolved, requires a coordinated input from many participants with different scientific, technical, business and sociopolitical backgrounds, including the input from the end-user, which is the client's personnel occupying individual workstations in office buildings. The proposed method of indoor air quality control offers a solution to the physical aspect of the indoor air quality issue, for which the building owners or their property management team is responsible. Once the physical aspect of indoor air quality is under control, other aspects which are more of a psychological nature can be resolved more productively.

In conclusion, the thesis offers a productive approach to the research and development related to indoor air quality in office buildings.

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F. Vaculik

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Nomenclatures

a	rate of diluent air, in changes per minute
AS	total air supply to the critical workstation, in cfm (L/s)
C	current concentration, in ppm
CI	initial concentration, in ppm
CLOA	concentration of contaminant in the diluent air, in ppm
CLV	potential instrument error, in ppm
dQg	dilution rate required, in cfm (L/s) per person
dQgmax	upper limit of the outdoor air supply error range, in cfm (L/s)
dQgmin	lower limit of the outdoor air supply error range, in cfm (L/s)
K	mixing factor
OAS	minimum outdoor air supply, in cfm (L/s) per person
PP	people present
Qd	dilution rate required, in cfm (L/s) per person
Qg	rate of air contaminant generation, in cfm (L/s) per person
Qgmax	upper limit of the potential instrument error
Qgmin	lower limit of the potential instrument error
r	ratio of concentrations on two concentration buildup curves with different initial concentrations, Equation 15
t	time between the occurrence of the initial and current concentration, in minutes
TAS	total air supply in ventilation options 1 and 2, in cfm (L/s)
TOA	total outdoor air supply in ventilation options 1 and 2, in cfm (L/s)
TLV	threshold limit value, in ppm
V _{cc}	outdoor air required in critical zone, in cfm (L/s) per person
Σ V _{on}	sum of minimum outdoor air into all workstations, in cfm (L/s)
Σ V _{cc}	total outdoor air flow, in cfm (L/s)
V _{cc}	supply air required into critical workstations, in cfm (L/s)
Σ V _{cc}	total air supply in cfm (L/s)

Definitions

Critical Workstation: a workstation with the smallest amount of supply air.

Mixing Factor: expression of ventilation effectiveness.

Non-Critical Workstation: other than a critical workstation.

Outdoor Air: Air with contaminant concentration no higher than specified by the ventilation standard.

Return Air: air which has absorbed contaminants in the workstations and on the way to and from them, and is being returned to the air handling system.

Supply Air: mixture of outdoor and return air which is supplied to the workstations.

Ventilation Effectiveness: effectiveness with which the air contaminants are removed from the workstations by outdoor air.

Workstation: a part of office floor area occupied by one person.

1.0 BACKGROUND

Air quality in buildings is not a new issue. Related studies were conducted as early as 1714. None of the work since that time, however, has had an impact as significant on the way we deal with the air quality issue today, as did the chamber studies conducted in 1930s by Yaglou et al. (1936).

Based on Yaglou's work, ASHRAE has established air quality criteria for various types of occupancies, and used them in its standard 62-1973, as well as in all the consequent revisions.

The air quality issue became very visible in the late 1970s and early 1980s. There were several reasons for that. In the 1970s, most of the new office buildings on this continent were designed to be fully air conditioned. The buildings also became much larger, both in their floor area and in their height. This increased floor size and building height resulted in a design concept of sealed windows and in a dependence on mechanical ventilation. In that period of time, many new materials were installed in office buildings without full appreciation of their chemical stability, and the impact of their out-gassing process on people.

Into this situation in office buildings came the worldwide oil crisis. Overnight, energy became the most important issue, if not the only issue, in the HVAC industry. Energy conservation measures were rapidly implemented into all facets of daily life. Office buildings were not exempted. The management of existing buildings as well as the design and construction of new ones was affected. Many retrofit projects of existing buildings were initiated to reduce the lighting levels, shorten operation hours and cut ventilation rates. The occupants of these buildings were accommodated in yet smaller cubicles forming part of the open floor concept, which was the architectural fad of the era.

The energy conservation program has made great strides in reaching its main objective of reducing energy consumption. In many instances, however, it went too far. The indoor air quality, as a result, became a problem due to the reduced ventilation rates.

Indoor air quality in office buildings is not a health issue, but rather a comfort issue impacting on productivity. Therefore, it is hard to compete for funds for indoor air quality related research, unless there is a public outcry. In the early 1980's, such a situation developed. The air quality became a public issue, and as a result many in-depth studies of air quality in office buildings, institutional buildings and family dwellings

have been conducted. These studies have indicated that a new, more technically intensive, approach to the design of buildings and their operation is needed.

Scientists responded by re-grouping their resources and re-directing their efforts from the high profile issue of energy conservation into a low key issue of energy efficient control of the indoor environment, including energy efficient control of air quality. The Air Pollution Control Association, together with ASHRAE formed a new technical association called Indoor Air Quality (IAQ). ASHRAE itself published an official statement on indoor air quality, and initiated a new review of its ventilation standard. The review has already been concluded and commented on by the general public. The newly revised standard 62-1981R based on this development is expected to be published shortly as a new ventilation standard ASHRAE 62-1987.

Scientists have responded positively and rather quickly. This is not the case, however, with the application engineers. There is a prevailing attitudinal problem in the industry which must first be resolved. Traditionally, the engineering efforts were predominantly channeled towards the design and construction supervision of buildings and towards the design and installation of HVAC equipment. As a result, very few engineers in the HVAC field practice as plant engineers in the commissioning, operation and maintenance phases of the delivery process. This creates problems in finding solutions to the air quality issue.

Not all aspects of the air quality issue can be resolved in a laboratory or in a design office. The final touch must be applied in a day-to-day operation. Since air quality control is not a simple technical task, there is a need for professional engineers to provide technical support to the property managers for as long as the building is producing a rental income.

The following presentation is intended to support the argument of the presently inadequate engineering support to property managers both in the private and public sectors, including the federal level. To argue this point more effectively, the presentation is made from the end product point of view, which is the point of view of the client who is paying the rent, as well as the point of view of the property manager who delivers the end product.

2.0 THE ISSUE OF AIR QUALITY

2.1 The End-Product Approach

The experience of the early 1980's shows that the air quality issue is judged by the public, not according to the research and development efforts in a laboratory, nor according to the planning activities in a design office, but according to the actual results in an occupied workstation. The clients, occupying workstations in an office building, consider the air quality to be one of the most important components of their accommodation.

Accommodation is a commodity which the clients receive on a continuous basis, and which is produced on a continuous basis by a property management team. Property management teams are headed by property managers, who are real estate professionals, usually with a non-technical background, and who are supported by their building operating and maintenance staff. The accommodation is, therefore, the end-product of the property management team.

The end-product is defined in an accommodation agreement by various performance and quality criteria, including the criteria of indoor air quality. The property manager's responsibility is to ensure that the end-product's performance or quality criteria are met during occupied hours. To fulfill this responsibility effectively, the property management team needs a practical quality control method for each one of the end-product components. Unfortunately, there are many components of accommodation for which a quality control method is either not practical or not available. In these cases, the property management teams have no choice but to rely on subjective techniques based on the perception of client's personnel. This is a disadvantage in the process of mitigating complaints about a sub-standard quality of accommodation.

Indoor air quality is one of the components of accommodation for which there is no practical method of quality control available, and for which a new CO₂ method is proposed by this thesis.

To introduce this method in proper perspective, let us first look into the nature and complexity of the air quality issue, then review the various air contaminant sources, after that, the concept of ventilation effectiveness will be assessed, and different interpretations of the ventilation standard examined. All this is presented from the end-product point of view, in order to fully convey all the benefits of the new CO₂ method to the property management team and to the clients, who are the users of the end-product, which is the accommodation.

2.2 The Nature and Complexity of the Air Quality Issue

Typical occupants of office accommodation spend about 80% of their total time indoors: in an office building, in a car, on a bus, on a train, in a community centre, in a restaurant, or at home. Approximately one quarter of that time is spent in the office building: in the workstations, meeting rooms, cafeteria, etc. The issue of air quality indoors is therefore very important to the occupants, and because of that, the air quality issue in office buildings is very important to the property management team.

The perception of air quality in office buildings is also affected by the air quality in other indoor spaces, where the occupants stay proportionally a much longer part of their day, week, or year. Nevertheless, how this quality is perceived should not have an effect on the actual air quality in buildings, if the air quality is measured by an objective method.

The perception of air quality is also affected by other related components. They either form part of the accommodation itself; such as the room temperature, humidity, illumination, air motion, workstation size and layout, acoustic privacy, and aesthetics, etc., or they form part of the psychological environment in which client's personnel must perform their work. All the task related stresses, the employee-management related stresses, family and community related stresses, physical and mental fitness benefits, medical history related issues, including various allergies, form this psychological environment.

The property management team is responsible for all components of the accommodation that are of the physical nature, while the components of psychological and physiological nature are the responsibility of the client's management. Obviously, there are many gray areas in this division of responsibility as related to the air quality issue, since many of the components of the issue interact with one another.

2.3 The Situation in the HVAC Industry

The above components of accommodation each affect the perception of air quality to an unknown degree. When faced with the task of assessing the air quality without an objective control or measurement method, the property management team finds very little engineering support. There are not enough engineers, who practice in the field of plant engineering in the office accommodation industry, who would provide the property management team with solutions, which would ensure compliance with the ventilation standard, and which would, at the same time, be

energy efficient.

The property management team needs to be provided with appropriate quality control methods, with suitable operation and maintenance documentation, and with regular technical support throughout the life of the facility. The members of the HVAC industry, who should provide this needed service, are not properly equipped for this task. The industry is concentrating its efforts mainly on the design and construction phases of the life cycle. There is a basic economic reason for that. The initial design and construction cost is relatively small, forming about 1/8 of the total life cycle cost, but it offers better chances of survival in the competitive world. This is due to the relatively short time needed to design and construct a building and a relatively larger profit margin for the various HVAC industry members as opposed to a 40 to 50 year period in which the plant engineering services are needed at irregular intervals.

Consequently, most of the engineering expertise is involved in the design and construction whereas almost no engineering expertise is used in the commissioning, operation and maintenance. This creates for the industry an isolation from the end-product. The designers seldom have, are given, or ask for the opportunity to verify their assumptions in the real life situation, and as a result their assumptions may not reflect the real life situation as they had anticipated. This is probably the reason why the technical information about the CO₂ method, which has been available for some time, has not yet been exploited to benefit the property management team and the client's personnel, the users of the end-product.

2.4 Air Contaminants

The new CO₂ method of air quality control, presented in the following section, is based on a method of controlling concentration of air contaminants by controlling the concentration of CO₂, which is acting as a surrogate representative of all contaminants. In order to appreciate how this surrogate method works, let us first review what kind of air contaminants are normally found in office buildings.

Air contaminants can emanate from three different sources:

- people,
- processes, and
- building materials and furniture.

Depending on the source, the process of contaminant generation can be described as follows:

- people and processes generate air contaminants during occupied hours only, because processes generally cease when the people leave;
- building materials and furniture generate air contaminants continuously, although the rate of generation declines in time as the out-gassing slows down.

There is a great need for research in this area. Very little is known about many of the air contaminants already identified, and it is hard to predict what contaminants will be generated by the future building materials, future furniture materials, and future office process equipment.

There is a need to know the generation rates, the acceptable comfort level and health levels of each of those air contaminants both when present alone, and when combined with other air contaminants, or other physical, physiological or psychological sources of stress.

2.5 Ventilation Effectiveness

Air contaminants generated in office buildings can be controlled by several methods. The most effective method is to eliminate the contaminant source. However, this is not always possible. The next method with respect to its ventilation effectiveness is the method of local ventilation. This method is applicable to the control of contaminants generated by processes, if their sources can be brought into a confined local area within a larger floor area, or into an enclosed room.

Most commonly, contaminants in an office building are controlled by the least effective method, the method of general ventilation. This method is based on a displacement process of contaminants by outdoor air. Outdoor air is expected to purge air contaminants by displacing them in the building, while leaving behind a residue of contaminants at or below an acceptable level of concentration. The dilution process needs a certain flow of outdoor air which is always more than if the air contaminants mixed with the outdoor air perfectly. Since in actual applications, the air contaminants and the air do not behave as ideal gases, more than the theoretical outdoor air supply is needed. Therefore, it is useful to establish an expression of ventilation effectiveness. It should be expressed as a ratio of the actual diluent air flow to the theoretical air flow. The ASHRAE Handbook, 1980 Systems, Chapter 21, Industrial Ventilation (ref. #2), calls this expression a mixing factor K . It is proposed to adopt the concept of mixing factor K also in the general ventilation method, for reasons of consistency.

Figure 1 shows a typical ventilation arrangement in office workstations. The following eight parameters or sub-processes form part of and influence the process of general ventilation:

- 1 outdoor air quality
- 2 outdoor air quantity brought in
- 3 mixing chamber effectiveness
- 4 degree of supply air mixing
- 5 diversity of supply air delivery
- 6 penetration of supply air
- 7 effectiveness of contaminant removal
- 8 return air mixing

For all the above parameters there is a need to know to what degree the mixing of air contaminant with the outdoor air is incomplete, to establish the overall expression of a ventilation system effectiveness. This information will be useful for determining the amount of extra air required to do the expected ventilation task.

The mixing factor K can also be useful for expressing the effects of configuration of workstations on the dilution process of air contaminants. The mixing factor K could be conveniently used to reflect the ability of the air handling system to penetrate down to the desktops.

Substantial further research is needed in this area before the air patterns within workstations can be accurately established and accurately modelled for a computer solution.

2.6 Ventilation Standard

Although aware of the need for additional research in the complex issue of air quality, ASHRAE has taken the initiative to use whatever available technical knowledge there is and formulate a standard for the industry which would bring about at least some consistency into air quality control. They have succeeded in more than that. In the first issue of the standard, ASHRAE 62-1973 (ref. #3), which was published when energy was cheap, the prescribed ventilation rates were generous enough to more than satisfy the air quality requirements while providing a big margin of safety for errors in the control of ventilation and air conditioning systems.

When the oil crisis arrived and fuel prices escalated, the ventilation rates were reduced in the standard's next issue, ASHRAE 62-1981 (ref. #4), down to a bare minimum. This made apparent the errors in HVAC system operation and controls.

The latest revision of the standard, ASHRAE 62-1981R (ref. #5), provides a solution which is more realistic. It also offers a guide for applying the requirements of the standard in a proper way.

In all its revisions, the ASHRAE ventilation standard defines air quality in terms of a minimum outdoor air quantity supplied for each type of occupancy either in cfm per person or cfm per square foot (L/s per person or $L/s \cdot m^2$) of occupied space. The prescribed outdoor air quantity to be supplied is expected to maintain an acceptable comfort level of indoor air quality. This definition of indoor air quality presents a great challenge to the property management team, for several reasons.

Reason 1: The expression of acceptable comfort level needs to be defined more precisely. The latest revision, ASHRAE 62-1981R (ref. #5), defines it as a level that is fully acceptable to 80% of the occupants. This definition obviously triggers a whole series of questions, for example: how is the comfort level measured for long term exposure; who is included in the sample, the healthy only, or the chronically ill too; how to define a healthy person, etc.

Reason 2: There is a lack of understanding of the synergy of two or more air contaminants, or the synergy of air contaminants and other sources of stress of either physical or psychological nature.

Reason 3: The expression of the air quality in terms of minimum outdoor air quantity creates a problem, because there is no direct method of measuring the outdoor air flow forming part of the supply air flow in conventional systems.

Reason 4: There are three possible ways of interpreting the minimum outdoor air to be supplied for the total building, as explained below. Two interpretations could be derived on the basis of the current standard ASHRAE 62-1981 (ref. #4), and the third one from the latest revision of the standard ASHRAE 62-1981R (ref. #5). In the following section, they are also referred to as three ventilation options.

2.7 Ventilation Options

Ventilation option 1, preferred by the designers, is based on the calculation of total outdoor air supply into the building according to the following equation:

$$TOA = OAS * PP$$

(1)

where: TOA = total outdoor air supply in cfm (L/s)
 OAS = minimum outdoor air supply in cfm (L/s)
 per person
 PP = people present

This option results in the most energy efficient solution. Unfortunately, it does not provide for a compliance with the standard in critical workstations. The reason for that is, that the supply air is distributed into the space with a diversity equal to the diversity of the cooling load. Consequently, the outdoor air, being distributed with the same degree of diversity causes some of the workstations to be over-ventilated, which is not a problem, but the rest of them under-ventilated, which is a problem. An argument for this interpretation is that the air will eventually remove the required amount of air contaminant. This argument is good on a scale of total building, but that is not the scale on which the property management team receives complaints of sub-standard air quality.

Ventilation option 2 reflects the second interpretation, which is preferred by the clients. The total outdoor air supply into the building is calculated based on the percentage of outdoor air required in a critical workstation.

$$TOA = TAS * (OAS / AS) \quad (2)$$

where: TAS = total air supply by the air handling unit in cfm (L/s), and

AS = total air supply to the critical workstation in cfm (L/s).

This produces a solution where all critical workstations are ventilated according to the standard and all other workstations are proportionately over-ventilated. This is not an energy efficient ventilation option (for a mechanical cooling mode of operation).

Ventilation option 3 is based on Equation 6-1, which is used in the latest revision of the standard 62-1981R (ref. #5).

$$\frac{V_{out}}{\sum V_{out}} = \frac{\sum V_{out} / \sum V_{out}}{1 + \sum V_{out} / \sum V_{out} - V_{out} / V_{out}} \quad (3)$$

where:

- V_{oe} = total outdoor air flow, in cfm (L/s)
- $\sum V_{oe}$ = total supply air, in cfm (L/s)
- $\sum V_{on}$ = sum of minimum outdoor air into all workstations, in cfm (L/s), (at 20 cfm or 10 L/s per person)
- V_{oc} = outdoor air required in critical zone, in cfm (L/s), (at 20 cfm/person)
- V_{sc} = supply air required into critical workstation, in cfm (L/s)

This equation has been adopted by the ASHRAE standard revision committee. The meanings of all the terms used in this equation are schematically illustrated in Figure 2.

The equation allows the calculation of the total outdoor air on the premise that the ventilation effect in a critical workstation in a multi-zone ventilation situation is equal to the ventilation effect in that workstation when ventilated as an isolated entity by the prescribed minimum outdoor air quantity. The result is a solution ensuring compliance with the standard in all workstations in the most energy efficient manner.

The effect of this approach is that the supply air to the critical workstation purges a relatively higher concentration of air contaminants than does the air supplied into the other workstations. This results in a mixed return air, which has still some ability to purge the air contaminants, due to the cleaner return air from the other than critical workstations. This mixed return air is then further mixed with outdoor air into a new supply air, the cleaning ability of which, in a critical workstation, must be such as if the critical workstation is ventilated by its own dedicated system which supplies the minimum outdoor air as given by the standard. This condition requires less outdoor air than calculated in option 2, and more than in option 1. For derivation of equation 3 refer to Appendix A.

All three ventilation options, or interpretations of the ventilation standard, are discussed in greater detail in the following sections.

2.8 Verifiability of the Ventilation Standard

The ASHRAE standard prescribes indoor air quality by a minimum amount of diluent air obtained from outside, which must meet

certain criteria for outdoor air. The minimum outdoor air is introduced into workstations by the air-handling system, which is tasked to perform two functions: temperature control and air quality control. Presently, there is no method in operation which could measure directly in the specified terms the amount of outdoor air in the total supply air stream arriving into an individual workstation.

2.9 Summary

This section has presented the air quality issue from the point of view of the end-product user and from the point of view of the property management team. The air quality is seen as part of the client's accommodation which is produced and delivered by the property management team in accordance with criteria of an accommodation agreement.

The nature and complexity of the air quality issue requires a departure from the traditional approach in the HVAC industry. More engineering input is needed in the operation, maintenance and commissioning. A new approach is also needed to co-ordinate research and development efforts in this area.

Ventilation effectiveness needs to be defined for the method of general ventilation. It is proposed to adopt the concept of a mixing factor K , which is to be used in industrial applications for the method of local ventilation.

The ASHRAE ventilation standard could be interpreted in three possible ways. That creates problems for the property management team.

3.0 THE CO₂ METHOD

The new CO₂ method of indoor air quality control is based on controlling the concentration of air contaminants by controlling the concentration of CO₂, which is acting as a surrogate representative for all contaminants in an office building.

The rate of CO₂ generation by people has been known for quite some time. The ASHRAE Standard 62-1981 (ref. #4), refers to this rate in its instructions for conversion of outdoor air quantity into CO₂ concentration. Also available for quite some time are the instruments for measuring CO₂ concentration. No one in the HVAC industry, however, has shown interest enough to put these two available bits of information together to produce a device for effective control of the indoor air quality on a real time basis.

All the mathematical expressions on which the new CO₂ method is based are presented in the following text. Also presented is an analysis of instrument errors, and a guide for preparation of air quality control strategy for office buildings.

3.1 Steady State

Although a steady state situation is seldom reached in a typical office building, for purpose of comparing one ventilation strategy with another, and for purpose of comparing ventilation performance in one office building with ventilation performance of another, it is convenient to express CO₂ concentration at steady state.

The first expression used in this method, therefore, is the steady state expression. It has been adopted from the industrial ventilation application as described in ASHRAE Handbook, 1980 Systems, Chapter 21 (ref. #2). It is derived from a volumetric definition of concentration of one fluid present in another after they have mixed with each other to a degree of imperfection expressed by the mixing factor K. The expression describes a situation in which a constant dilution rate and a constant contaminant rate produce a constant concentration after a considerable period of time of about 10 hours.

$$Q_d = \frac{Q_g * K}{TLV} \quad (4)$$

where: Q_d = dilution rate required, L/s*person (cfm/person)

Q_g = rate of contaminant generation, L/s*person (cfm/person)
 K = mixing factor
 TLV = threshold limit value in ppm (usual range of 600 to 1200 ppm)

Note: If TLV is expressed in ppm, then its value shall be divided by a factor of 10^6 , to agree with the other units.

Threshold limit values are published by the American Conference of Government Industrial Hygienists as the health and safety values for long term exposures of 40 hours a week, in an industrial environment.

The above expression is applicable for contaminants which are not present in the outdoor air being used as the diluent air. If the contaminants are present, the expression must be modified as follows:

$$Q_d = \frac{Q_g * K}{TLV - CLOA} \quad (5)$$

where: $CLOA$ = concentration of contaminant in the diluent air, ppm (about 340 ppm of CO_2), see also note to equation 4.

The significance of equation (5) is that the concentration TLV of two streams of gases, Q_g and Q_d , is increased by the amount of concentration $CLOA$ of gas Q_g in GAS Q_d before the mixing took place, i.e. shift in effective zero.

For the control of indoor air quality in office buildings it is necessary to replace the threshold limit value with a comfort level value. The expression then takes on a form:

$$Q_d = \frac{Q_g * K}{CLV - CLOA} \quad (6)$$

where: CLV = comfort level value in ppm, see note to equation 4.

The method uses known rates of CO_2 generation by people in various types of activities (ref. #4), which are as follows:

0.0036 L/s (0.075 cfm) for people at rest,
 0.0050 L/s (0.010 cfm) for deskwork activities, and
 0.0072 L/s (0.015 cfm) for benchwork in a factory.

As noted in equation 5 and 6, application of this method is based on a known CO_2 concentration in the outdoor air, which could be obtained by a measurement, and is intended to allow provision of the quantity of outdoor air per person which is prescribed by the ventilation standard.

The prescribed minimum outdoor air quantity is established by a consensus among the experts on this topic from within ASHRAE. The air quantity is generous enough to compensate for the present uncertainty of the ventilation effectiveness. The mixing factor K can therefore be omitted from the last expression, as long as it could be ensured that the air velocity in every workstation is between 2 and 6 in/s (50 and 150 mm/s), (ref. #6).

The comfort level values may be obtained by re-arrangement of equation 6 for a single workstation application ($PP=1$):

$$CLV = CLOA + \frac{Qg}{Qd} \quad (7)$$

or by a re-arrangement for a multiple occupancy application.

$$CLV = CLOA + \frac{Qg * PP}{Qd} \quad (8)$$

where: PP = people present.

3.2 Transient State

During the silent hours, when the building is unoccupied, the concentration of CO_2 will decline toward a new, lower value. As people enter, the declined value will become the initial concentration for the day. From that moment on, the concentration will gradually buildup to a steady state level over a considerable time. During that time, the CO_2 concentration will be in a transient state, from the initial value towards the steady state value. The CO_2 concentration buildup will follow an exponential curve calculated from the following expression published in the Supplement to the National Building Code of Canada 1985,

Article (4), Dilution (ref. #7).

$$C = CLV - (CLV - CI) * \exp(-a*t/K) \quad (9)$$

where:

CI	=	initial concentration, ppm
C	=	current concentration, ppm
a	=	outdoor air in changes per minute
t	=	time between the occurrence of the initial and current concentration, min

As will be demonstrated in the following sections, the concentration change of CO₂ in time follows an exponential curve, a simple form of which is followed if all of the occupants enter the building in the same time and if all of them produce CO₂ uniformly at a given rate throughout the day. In most cases this will not be so, which results in modifications to the exponential curve.

The CO₂ method is based on the steady state equation (8) and the transient equation (9). These two equations are used to translate outdoor air quantity, which is a non-verifiable indicator of air quality, into a verifiable indicator of CO₂ concentration. Application and manipulation of these equations is presented in the following two sections.

3.3 Instrument and Its Accuracy Analysis

The accuracy of the application of the CO₂ method depends on the accuracy of instruments which measure CO₂ concentration. The instrument proposed to be used in this method shall be of a non-dispersive infrared absorption type. Specification guide for CO₂ Metres is presented in Appendix F. The principle of CO₂ measurement by infrared analyzer is explained in ASTM Special Technical Publication 555 (ref. #8).

Let us now examine the way the potential instrument error of the measured variable(s) relates to the potential error of the controlled variable, the outdoor air quantity.

If two instruments are used, then the combined potential instrument error of a "±" value can be expressed as:

$$dQ_g = (Q_g \text{ max} - Q_g \text{ min}) * 2^{0.5} \quad (10)$$

where: dQ_g = potential instrument error
 $Q_g \text{ max}$ = upper limit of the potential instrument error range
 $Q_g \text{ min}$ = lower limit of the potential instrument error range

If the outdoor air concentration is constant and known, which is so in most cases, then only one instrument need be used, and its potential error is:

$$dQ_g = Q_g \text{ max} - Q_g \text{ min} \quad (11)$$

Equation (11) signifies that an accuracy of, for example, ± 50 ppm, is expressed as a potential instrument error of as much as $50 - (-50) = 100$ ppm.

To convert the instrument error into air quantity error at any given steady state situation, the following expressions derived from equations (6) and (11) can be used. The mixing factor K is omitted from equation (6) for reasons stated above.

$$dQ_d = \frac{dQ_g}{CLV - CLOA} \quad (12)$$

$$Q_d \text{ max} = \frac{Q_g \text{ max}}{CLV - CLOA} \quad (13)$$

$$Q_d \text{ min} = \frac{Q_g \text{ min}}{CLV - CLOA} \quad (14)$$

where: dQ_d = potential error of the outdoor air quantity
 $Q_d \text{ max}$ = upper limit of the outdoor air supply error range
 $Q_d \text{ min}$ = lower limit of the outdoor air supply error range.

See also note for equation 4.

The impact of instrument error on the error of outdoor air quantity is demonstrated by the following two examples. In the first example, Figure 3, the potential instrument error is 100 ppm, which means ± 50 ppm, and in the second example, Figure 4, the

potential error is 200 ppm, ± 100 ppm. The first example represents an instrument of high accuracy, the second example represents instruments of commercial accuracy. In both examples the instrument is used to measure the CO_2 concentration of indoor air only.

The error analysis of both examples was performed by a computer program specifically written for this purpose. A line-by-line listing of this program is shown in Appendix E. The program is written for an IBM PC and is available in two versions: the ERROR.BAS version is to be used with a printer, and the ERRORS.BAS version does not need a printer.

The printout of calculations supporting this analysis is given in Table 1 for the ± 50 ppm instrument. The calculated potential errors, both absolute and relative, need to be related to the average value of minimum outdoor air supply. The following observations can be made from these calculated errors for a range of situations:

- a) the error grows larger the closer the controlled concentration is to the concentration of diluent air of 340 ppm, see Figures 3 and 4,
- b) the mean value of error is always on the 'safe' side of over-ventilation, see Figure 3,
- c) for a reasonable reliability of this method, it is necessary to have instruments with a high degree of accuracy,
- d) the supply air stream is the worst location for the CO_2 sensor, since there the CO_2 concentration is the lowest,
- e) the best location is in the critical workstation, although that may not always be practical, and
- f) the return air stream location offers relatively good accuracy and allows for servicing the sensor away from the occupied space.

These observations will be used when the control strategy is formulated. Now, let us see how the accuracy of the CO_2 method for air quality control in office buildings could be improved.

3.4 Improvements in Accuracy

Each air handling unit with a free cooling cycle is equipped with a thermostatic control loop, including all necessary instru-

ments, to control its mixed air temperature. This control loop is normally activated when the unit is in a free cooling mode of operation and it is by-passed when the unit is in a mechanical cooling mode of operation.

If this control loop were to be used also during the mechanical cooling mode of operation, then the mixed air temperature would change in accordance with the changes in outdoor temperature. For example, if the return air temperature is 26 deg C (76.9 deg F) and the outdoor temperature is 28 deg C (82.4 deg F), then the mixed air temperature would be 26.4 deg C (77.5 deg F), if the desired outdoor air quantity equal to 20% of the total air supply is included in the mixed air.

If the thermostatic sensor accuracy is ± 0.5 deg C (1 deg F), then the mixed air temperature can in actuality be anywhere in the range of 26.4 ± 0.5 deg C (77.5 ± 1 deg F), see Figure 5, while reading is 26.4 deg C.

When this accuracy of the measured variables of return air, outdoor air and mixed air temperatures is projected into the accuracy of the controlled variable, i.e. the outdoor air quantity, the result is found to be unacceptable due to the proximity of the return and outdoor air temperatures, see Figure 6.

By plotting the outdoor air supply errors against the outdoor and return air temperature difference, it is possible to find a suitable difference between the return air temperature and the outdoor air temperatures, at which the outdoor air quantity error becomes acceptable for a given instrument accuracy, see Figure 7.

For a given sensor accuracy, the accuracy of control of the outdoor air quantity can theoretically improve with greater difference between return and outdoor air temperatures. There is a limit to that, however, which is imposed by a natural phenomenon of stratification in the ducting, which occurs at larger air temperature differences.

In such situations, a grid of instruments should be installed into the mixed air stream, as suggested by Figure 8. Both temperature and air velocity readings must be taken at each point of the grid. Since each one of the instruments would have its own instrument error, the gained accuracy would be lost again, because the mean mixed air temperature and mean velocity would have to be calculated.

From this discussion it can be observed that a reasonable degree of outdoor air supply accuracy can be achieved in a small temperature interval. This idea could be exploited for purposes of calibration of the CO₂ control loop.

3.5 Control Strategy

The objective of a control strategy is to ensure compliance with the requirements of the ventilation standard during occupied hours in a most energy efficient manner. The strategy should rely on a minimum or no day-to-day input by the property management team.

Before discussing the guiding principles for the preparation of a control strategy to be used in conjunction with the CO₂ method, let us establish first where and when the method is applicable.

Air handling systems with fixed outdoor air supply, such as the compartmental air handling units, do not need the CO₂ method for day-to-day control at all. The method, however, could be used in such buildings for commissioning purposes to establish the compliance with the ventilation standard, and perhaps also for the ensuing performance verifications when complaints of sub-standard air quality are reported or when changes to the office layout are made.

Air handling units with a free cooling cycle provide more than the required air quantity when in the free cooling mode of operation, so they do not need the CO₂ method during that time. During the mechanical cooling cycle, however, these units provide only a minimum supply of outdoor air in order to minimize energy consumption needed for mechanical cooling. This is the mode of operation, where the CO₂ method is applicable. The method may also prove to be useful in finding the proper balance point between compliance with the ventilation standard and energy cost, which is important to the property management team.

In most office buildings, the washroom exhaust system(s) capacity, or rather the volume of outdoor air replacing the exhausted air, represents a substantial portion of the required minimum outdoor air quantity. If the required outdoor air quantity is calculated according to equation 1 in ventilation option 1, as defined in section 3.0, then the outdoor air supply making up for the washroom exhaust system(s) may be sufficient. If on the other hand, ventilation option two or three is followed, then the required minimum outdoor air quantity is larger than the make up air for the washroom exhaust system(s). Consequently, if ventilation option two or three is to be used, then the CO₂ method will be needed in most office buildings at times when their air handling systems are in a mechanical cooling mode of operation.

Based on the above observations, the CO₂ method will be most effective once the number of people who have entered the building, exceeds the number which would be served with the outdoor

air supply needed to make up for the washroom exhaust system. That particular time should be established through observations of the arrival pattern and used for starting the clock in the transient state expression. Similar observations shall be made about the arrival pattern after lunch, to establish the re-starting time of the clock in the transient expression for the operation in the afternoon.

Since the accuracy of the CO_2 method improves as the calculated set point moves closer to the steady state concentration, the controller should be programmed to remember the outdoor air damper position at the time of best accuracy, recall it, and use it while the accuracy is lower in the next morning or shortly after lunch.

These several points shall be used as a guide for preparation of a control strategy for an actual building. They are oriented towards the control of air contaminants generated during the occupied hours. There is another side of ventilation performance in office buildings, however, which is concerned with the control of contaminants generated continuously by building materials and office furniture. This side of the ventilation performance is related to the purging process of the building in the pre-occupancy hours. An example of control strategy preparation for the purging cycle is presented in section 5.0

3.6 Summary

In this section, a proposed new method of air quality control is presented. It is a method which can ensure a compliance with the ventilation standard in an energy efficient manner. The method is based on control of CO_2 concentration in the building, which represents certain air quality achieved by a purging process of the indoor air contaminants with a prescribed amount of outdoor air.

Equations of steady state and transient state for correlating minimum outdoor air quantity into concentration of CO_2 are presented and the viability of this method is also discussed. Two examples of instrument accuracy demonstrate the applicability of the method to air quality control in office buildings. The errors of instruments can be minimized under certain conditions by interfacing the mixed air temperature control loop with the CO_2 concentration control loop.

The objectives of the method are to ensure a compliance with ventilation standard in a most energy efficient manner.

4.0 THE COMPUTER PROGRAM

This section explains the applicability and outlines the application process of the CO₂ method which is proposed to be used to control air quality, as well as to commission the ventilation performance in office buildings. The following explanation is made as an example of a typical office building.

The example includes an analysis of all variables and an explanation of their impact on the building's compliance with the ventilation standard. A computer program in BASIC programming language has been prepared for purpose of this analysis. A floppy disc with this program is attached. The program is called CO2S.BAS. Its flow diagram is shown in Appendix B, its line-by-line listing is shown in Appendix C and some users instructions are given in Appendix D.

4.1 An Example

For the purpose of presenting the material of this section in a more comprehensive fashion, an office building of medium size, representative of office buildings less than twenty years old was selected as an example. The building's physical and operational characteristics are shown in Table 2.

The example is based on an assumption that all people are involved in activities that cause them to generate CO₂ at a rate indicative of sedentary type of work.

The computer program CO2S.BAS has the ability to analyze each one of the variables and explore their individual or combined effects on the resulting ventilation effectiveness.

4.2 Interpretations of the Ventilation Standard

As already mentioned in the previous sections, there are three possible interpretations of the ventilation standard at the present time. The first two are from the current standard ASHRAE 62-1981 (ref. #4), and the third one is from its latest revision 62-1981R (ref. #5). They are identified in the CO2S.BAS program as ventilation options number 1, 2 and 3.

Once the latest revision of the ventilation standard is published in its final version, and adopted by the industry, the first two interpretations will no longer apply.

The current standard requires a minimum outdoor air rate of 5 cfm (2.5 L/s) per person for nonsmokers and 20 cfm (10 L/s) per person for smokers. An accepted practice for applying these requirements to office buildings stems from a recent survey. The survey indicates that in America, there are about 1/3 smokers and 2/3 nonsmokers among office workers. This rule may perhaps work on the total building scale, if the distribution of smokers is regular, but in many local situations it does not work. Its application causes administrative headaches for the property management team. Whenever there is a rearrangement of the occupancy, the ventilation performance must be reviewed and adjusted to suit. This rule is especially difficult to comply with in meeting rooms, conference rooms and board rooms.

If applied, it produces an average minimum outdoor requirement of:

$$\frac{(2 * 5) + 20}{3} = 10 \text{ cfm (5 L/s) per person}$$

For comparison purposes, all the possible combinations of smokers and nonsmokers, as well as all the possible interpretations of the current and revised standard are analyzed below to illustrate their different impacts on the ventilation performance.

The analysis is performed by using the feature number seven (7) on the program's menu called the "Outdoor air supply per person", see Table 3. A range of 5 to 20 cfm with steps of 5 cfm is sufficient. The computer calculates the steady state CO₂ concentration, changes of outdoor air per hour, and average outdoor air supply per person for each step within the selected range, as shown in Table 4.

By selecting number fifteen (15) on the menu, see Table 3, the ventilation option can be changed. The above number seven (7) routine needs to be repeated for each ventilation option. The following observations can be made from the above analysis:

In this particular example, ventilation option 1, as defined in section 2.7, will result in a steady state CO₂ concentration of 1,399 ppm, as shown in Table 4A; if the above rule for smokers and nonsmokers is applied, i.e. 10 cfm (5 L/s) per person. This CO₂ concentration is considered to be too high. Recent studies of office building ventilation in North America indicate that a CO₂ concentration of 1,000 ppm should be considered as an upper limit of acceptable ventilation performance. A good ventilation performance would be obtained if the rule was changed to 90% smokers and 10% nonsmokers, which does not reflect the present trend in attitude towards smoking.

If another interpretation of the current standard were to be used, which is reflected in ventilation option number 2, then the 1000 ppm limit could be achieved by providing a minimum amount of outdoor air at a rate of 6 cfm (2.8 L/s) per person, as shown in Table 4B. It should be noted that the actual average outdoor air supply in this ventilation option is substantially higher, close to 16 cfm (7.6 L/s) per person. This mode of operation would satisfy a mix of 10% of smokers and 90% of non-smokers. If the above rule of 1/3 and 2/3 were applied, the resulting concentration of CO₂ would be excellent, but energy inefficient.

The interpretation of the revised standard, which is reflected in ventilation option 3, is based on a uniform requirement of outdoor air supply of 20 cfm (10 L/s) per person, whether they smoke or not. The steady state CO₂ concentration, resulting from the above described analysis, is 796 ppm in this particular example, as shown in Table 4C. If only the 1,000 ppm limit were to be complied with, then the actual minimum outdoor air supply could be reduced to about 17 cfm (8.0 L/s) per person on average. This difference in the outdoor air supply could be considered as a built-in margin of safety for design and operational errors. This is an important observation which should be remembered when preparing a control strategy for an actual building, or when analyzing the extent of error of the CO₂ method.

4.3 Building Characteristics

Continuing with the same example, the impact of building size and interior office layout is analyzed next.

4.3.1 Floor Area

Building size is analyzed by the feature number one (1) on the program's menu, see Table 3. Investigation of a range of 50,000 to 150,000 square feet (4645 to 13940 m²) in steps of 10,000 square feet (5,000 m²) prove that this variable has no impact on the CO₂ concentration and on the average outdoor air rate per person. See Table 5. The changes of outdoor air per hour vary in accordance with the changes in building volume.

4.3.2 Ceiling Height

The same situation occurs when the impact of the ceiling height on the ventilation performance is analyzed by feature number two (2) on the program's menu, see Table 6. Ceiling height in

office buildings is usually between 9 and 12 feet (2.75 to 3.65 m), for reasons of construction economy. Ceiling height depends also on the return air arrangement. In cases, where the ceiling space is used for a return air plenum, the ceiling height needs to be measured to the under-side of the floor slab or the roof slab above. Allowances should be made for the ductwork and pipework taking up room in the ceiling space.

4.3.3 Number of Workstations and People Present

The next analytical feature, number three (3), on the program menu Table 3, can be used for the analysis of the office layout. Number of workstations does not affect ventilation performance, but number of people present does, as could be demonstrated by using the next analytical feature, number four (4). An investigation of the occupancy between 50 and 600 persons present in steps of 50 provides the following insight.

Analysis of ventilation option number 1, see Table 7A, proves the CO₂ concentration and the average outdoor air rate per person unchanged, while the changes of outdoor air per hour varies linearly with the number of people present. In ventilation option number 2, the situation is reversed, see, Table 7B. The first two indicators vary with the people present, while the third one, the changes of outdoor air per hour, remains constant. This is so due to the fact that the program assumes that the first person entering the building goes into a critical workstation.

In the third ventilation option, all three indicators of ventilation performance change with the number of people present, see Table 7C. It is important to observe and remember this relationship when preparing a ventilation control strategy for a specific building.

4.3.4 Workstation Size.

The next variable of the building to be analyzed is the size of the smallest, or critical, workstation. Its size should be normally in the range of 100 to 150 square feet (9.3 to 13.9 m²), and its impact, as could be seen in Table 8, on the ventilation performance is negligible. The size of workstation may, however, affect the air velocity at the desktop and thus affect the dilution action of air contaminants in the workstation. This could be expressed mathematically by a different value of mixing factor K, described in the previous section as a convenient expression of ventilation performance in a workstation. This computer program, however, does not take the K factor into account, for reasons explained above.

4.4 Operational Characteristics

The analysis will now concentrate on the variables of operational nature. The property management team may control these variables more effectively than the variables related to the physical building components analyzed above.

4.4.1 Air Supply to Critical Workstations

The analysis of the impact of the total air supply into critical workstation shows that ventilation performance is affected only in the case of ventilation option 2, due to the definition of total outdoor air supply in this option, see equation 2, see also Table 9. This observation is very important. In cases of ventilation option 1 and 3, the CO₂ method is easily applicable for either VAV (variable air volume) systems or constant air volume systems, because the ventilation performance indicators are not affected by the total air supply to the workstation. Ventilation option 2 would present a serious control challenge of measuring the air velocity in workstations in real time. The appropriate workstation would have to be selected experimentally to represent all workstations in a critical ventilation zone satisfactorily.

Several observations about the VAV systems should be made at this point. The ventilation effectiveness, as it has been proven by commissioning experience, depends on the air velocity at the desk level which needs to be established and maintained in a range of 50 to 150 mm/s (2 to 6 in/s). This is a difficult air balancing task with any overhead air supply system, but it may prove to be impossible with the VAV system. The established air velocity at the desk top level for one diffuser outlet velocity may not be maintained at other velocities with the corresponding operating range of a VAV box governing the diffuser outlet velocity. This engineering challenge may need to be solved by alternative means, such as a desk top fan. This fan could either be a separate unit or could be combined with a desk lamp. There are some side benefits offered by the desk top fan as well. It could provide additional speech privacy and extract heat generated by the lamp. These additional benefits may prove this alternative solution to be economically feasible, if carefully coordinated with the task oriented lighting system.

Some manufacturers are offering office furniture organised into clusters around a service column in which there is installed a fan providing the above functions. More research is needed in this area as already mentioned in the previous sections.

4.4.2 Outdoor Air Per Person

The next operational parameter is the rate of outdoor air per person, analytical feature number seven (7), Table 3. This variable has already been discussed at the beginning of this section. See also Table 4. Since the latest revision of the ventilation standard calls for 20 cfm (10 L/s) per person, smokers or not, there may seemingly be little use for this analytical feature. As shown in another section, this feature is important for the assessment of error of the CO₂ method. The other important use of this feature is in commissioning of ventilation performance.

4.4.3 Total Air Supply

The analysis of total supply air, feature number eight (8) on the program's menu Table 3, is useful for assessing the applicability of the CO₂ method to VAV systems, which have been popular since the early 1970's. Analysis should be performed for a range between 30% and 120% of the design total air supply, to cover all the possible part load situations.

An interesting situation develops with respect to the ventilation options, see Tables 10A, 10B and 10C. Ventilation option 1 shows no change throughout the part load interval. That makes the CO₂ method easily adaptable to it. Ventilation option 2, however, shows a dependence of the CO₂ concentration on the total air volume due to the specific definition of outdoor air, as expressed by equation 2. If the CO₂ methods were to be used with ventilation option 2, a flow sensor would need to be added to reset the control set point in relation to the change in total air supply. This sensor would introduce additional instrument error to the CO₂ method.

Ventilation option 3, reflecting the latest revision of ventilation standard 621981R, shows only a slight dependence of the CO₂ concentration on the total air volume. This is due to the specific definition of total outdoor air supply in this option, as expressed by equation 3. It could be observed that the design flow of 120,000 cfm (56,640 L/s), if used also as the design total air flow for the CO₂ method, would cause the method to err on the 'safe' side at lower loads and would cause a sub-standard ventilation for higher than design loads. An adjustment to the design total air flow could be made either manually or automatically according to the load of the hour on a day-to-day basis.

4.4.4 Outdoor Temperature

With respect to the CO₂ method, the most significant temperature of the mixing chamber is the outdoor air temperature.

In air handling systems equipped with a free cooling cycle the outdoor air changes per hour, as well as the average outdoor air rate per person, vary with the outdoor air temperature, see Tables 11A, 11B and 11C. For graphical expression of a similar example see Figure 19. The air changes per hour follow a hyperbolic expression with axes at zero outdoor air changes per hour and at the return air temperature. Control sequences of free cooling cycles do not normally use that portion of the curve which is above the supply air temperature.

In all three ventilation options, the free cooling cycle produces in the same building the same profile of outdoor air changes per hour.

4.4.5 Return and Supply Air Temperature

Analysis of the sensitivity of these two variables, by using features nine (9) and ten (10) of the program, see Table 3, prove that when in the mechanical cooling mode, the air handling systems provide the same ventilation performance regardless of the return air and supply air temperature variations. When in the free cooling mode, however, the changes of outdoor air per hour vary with the difference between return and supply air temperatures. These temperatures do not normally vary by more than ± 2 to ± 5 deg F (± 1 to ± 2.5 deg C), therefore the resulting modification of a free cooling diagram, as shown in Figure 19, are marginal. This observation may be useful for preparation of that part of the ventilation control strategy, which is related to the pre-occupancy purging of the building.

4.4.6 CO₂ Concentration Outdoors

This variable shifts the resulting steady state concentration of CO₂ in the same direction and by the same amount by which the outdoor CO₂ concentration has shifted, see Table 12. In locations, where outdoor CO₂ concentration is stable, no adjustment to the calculated set point is needed. Where the CO₂ concentration varies, there is also a need to install a CO₂ concentration sensor for measuring the outdoor concentration. This will result in an increased error of the CO₂ method by a factor of 20%.

4.4.7 Initial CO₂ Concentration

The transient state concentration of CO₂, in situations where the initial concentration is different from the outdoor concentration, will also follow an exponential curve. This curve is related to the exponential curve representing the transient state which starts with the indoor concentration equal to the outdoor concentration by a ratio r , where

$$r = \frac{CLV - CI_2}{CLV - CI_1} \quad (15)$$

where: CI_1 = initial concentration in case 1, equal to the outdoor concentration
 CI_2 = initial concentration in case 2, higher than the outdoor concentration
 CLV = concentration in steady state.

This could be analytically proven as follows, see Fig. 9 in and Table 13.

Step 1: A point on the curve of case 1 is related to the corresponding point on curve of case 2 by a ratio of distances of these two points from the concentration in steady state.

Conditions in Case 1: for $t = t_1$, $C = C_1$ and
 for $t = 0$, $CI = CI_1 = CO$.

Then:

$$CLV - C_1 = (CLV - CI_1) * \exp(-a*t_1/k) \quad (16)$$

Conditions in Case 2: for $t = t_1$, $C = C_2$ and
 for $t = 0$, $CI = CI_2$.

Then:

$$CLV - C_2 = (CLV - CI_2) * \exp(-a*t_1/K) \quad (17)$$

By comparing Case 2/Case 1:

$$\frac{CLV - C_2}{CLV - C_1} = \frac{(CLV - CI_2) * \exp(-a*t_1/K)}{(CLV - CI_1) * \exp(-a*t_1/K)} \quad (18)$$

According to equation 18, equation 19 is always true since the exponential members cancel.

$$\frac{CLV - C_2}{CLV - C_1} = \frac{CLV - CI_2}{CLV - CI_1} \quad (19)$$

This signifies that the ratio can be derived from the initial concentrations and the steady state concentration.

Step 2: Any point on the curve of case 1 is shifted by a constant time delay from a corresponding point on the curve of case 2.

Conditions of case 1: for $t = t_1$, $C = C_1$ and
for $t = 0$, $CI = CI_1 = CO$.

then again:

$$CLV - C_1 = (CLV - CI_1) * \exp(-a*t_1/K) \quad (20)$$

Conditions of case 2: for $t = t_1 - t_0$, $C = C_1$, and
for $t = -t_0$, $CI = CO$
for $t = 0$, $CI = CI_2$

then:

$$CLV - C_1 = (CLV - CI_2) * \exp(-a*(t_1 - t_0)/K) \quad (21)$$

Since the case 1 is equal to case 2, then combining equations (20) and (21) yields

$$\frac{CLV - C_1}{CLV - C_1} = \frac{(CLV - CI_2) * \exp(-a*(t_1 - t_0)/K)}{(CLV - CI_1) * \exp(-a*t_1/K)} = 1 \quad (22a)$$

$$\text{or} \quad \frac{(CLV - CI_2)}{(CLV - CI_1)} = \exp(-a*t_0/K) \quad (22)$$

and by substituting from equation 19, it follows that:

$$\frac{(CLV - C_2)}{(CLV - C_1)} = \exp(-a*t_0/K) \quad (23)$$

from which

$$t_0 = \frac{K}{a} * \ln \frac{CLV - C_0}{CLV - C_1} \quad (24)$$

This expression proves the point, and can therefore be used to calculate the extent of the delay.

4.4.8 Flexible Hours

In the morning, office buildings are usually occupied gradually over a period of one or two hours. The federal government has adopted a policy of flexible hours to positively respond to the call for solving traffic problems. As a result, in many federally owned and operated public buildings, the occupancy starts at about 7:30 a.m. and is completed by about 9:30 a.m.

Analytical feature number fourteen (14) of the program is provided with an automatic linear occupancy buildup formula to calculate the CO_2 concentration profile for any period of time needed for reaching the full occupancy when the door is open. Figure 10 and Table 14 show three cases, the first one with full occupancy at the outset, the second one with full occupancy reached in one hour and the third one with full occupancy reached in two hours.

An important observation should be made here. As soon as the full occupancy is reached in either of cases two or three, at the same time the CO_2 concentration profile becomes identical with the profile of case one. This is caused by the value of diluent air changes or outdoor air changes being variable until the full occupancy is reached, when the air changes become constant.

This is a very important observation for the control strategy preparation for actual buildings, as demonstrated in the next section.

4.4.9 Change in Metabolism

The program offers three levels of CO_2 generation rates related to three different levels of metabolism characteristic of three types of activities: at rest, at sedentary work and at benchwork. See Table 3, for the analytical feature number 16. All the above analyses were performed for the CO_2 generation rates corresponding to the sedentary type of activity. For comparison

purposes, it is interesting to see what happened when the intensity of activity changes. An analysis of the resulting steady state concentration for all three available CO₂ generation rates shows a drop of CO₂ concentration from 796 ppm, representing the sedentary activity, down to 668 ppm if everybody is at rest, and a rise to 997 ppm if everybody is engaged in manual work such as furniture moving.

More research is needed in this area to better understand how people behave throughout the entire workday. Is their metabolism changing according a certain pattern? Is the generation rate on average reduced and by how much? These are two of the several questions which need to be answered.

For the time being, however, a pragmatic approach to the application of the CO₂ method needs to be taken. Whenever people slow down, their generation rate of CO₂ will also slow down which would result in less ventilation requirement. This may be considered acceptable, since at that time less body odors would be generated as well. Conversely, if everybody worked harder than expected, that would mean more CO₂ generated which would result in more ventilation requirement. Again, this would automatically compensate for the additional body odors due to the extra activities.

4.4.10 Number of Workstations in Critical Zone

This variable has no effect on the ventilation performance in either of the three ventilation options, or the three possible interpretations of ventilation standard.

4.5 Board Rooms, Conference Rooms and Meeting Rooms

All the above analyses were performed for the ordinary office type of workstations, normally found either in enclosed offices or in an open office space arrangement. Let us now look into the ventilation performance in board rooms, conference rooms and meeting rooms, where the ventilation solution is different.

A certain flow of the supply air is assigned to each of these spaces for purposes of temperature control. By prorating the minimum outdoor air quantity from a critical workstation, a requirement for a minimum number of occupants can be calculated at which compliance with the ventilation standard can be ensured in these particular rooms. If this minimum number of occupants is less than the seating capacity in those rooms, additional ventilation is needed. That could be achieved by additional air taken from the return air plenum. The quantity of additional

air should be calculated as shown on the following example:

Meeting air supply	900 cfm (425 L/s)
Seating capacity	25
Air supply to a critical workstation	90 cfm (47.5 L/s)

From which:

$$\frac{900}{90} = 10 \quad \text{people can be present without any additional ventilation,}$$

and

$$(25 - 10) * 90 = 1350 \text{ cfm (637 L/s) of additional ventilation capacity shall be installed.}$$

Notes:

The meeting room may be used for a long slide presentation. At that time, the lights would be either dimmed or turned off. That could result in a reduced supply of air, in case the meeting room is serviced by a VAV box with no reheat. In that case, it is recommended to provide an additional ventilation capacity either by a two stage fan or by two fans. The second stage or combined capacity of the fans shall be at least 2250 (900 + 1350) cfm (1060 L/s).

The above example is applicable in situations, where people attending meetings come predominately from the same floor on which the meeting room is located. In cases, where the meeting rooms, board rooms or conference rooms are located on a dedicated floor, a special and more complex solution is needed.

4.6 Summary

This section explains how the CO₂ method could be applied to a typical office building by presenting results of analysis of sensitivity of all variables. Each one of the analyses is performed on a computer program written for this purpose.

The discussion starts with an explanation of the impact of the various possible interpretations on ventilation performance, which creates a complicated situation for the property management team. The situation will improve once the latest revision to the standard is published and adopted.

From the many variables analyzed, the most important ones are as follows.

The 'Air Supply to Critical Workstations' has no effect on the ventilation performance in workstations. This is important for the application of the CO₂ method to VAV systems. Similarly, the 'Total Air Supply' has only a slight effect on the ventilation performance, which could be very easily corrected when the CO₂ method is used in buildings with VAV systems.

The discussion then concentrates on the application of the transient state equation to the situations with different initial concentrations. Transformation equations from one such situation to another are given.

One of the most important variables is the 'Flexible Hours of Occupancy'. This variable is a key one to the ventilation strategy for morning operation. Its impact is presented in greater detail in the next section in the discussion about ventilation strategy.

The discussions are concluded with an example of application of the ventilation standard requirements to board rooms, conference rooms and meeting rooms. These rooms require a different ventilation solution.

5.0 A PILOT PROJECT

5.1 An Unsolicited Proposal

The VCI Controls Company of Ottawa has submitted an unsolicited proposal to the Department of Supply and Services to install a CO₂ control module in the Jeanne Mance Building in Tunney's Pasture, Ottawa. The proposal is based on the material presented in this thesis.

There are two reasons for selecting this particular building: The building has a relatively simple air handling arrangement, and it is equipped with a direct digital control system installed by the VCI Controls about two years ago.

5.2 Building Description

The building houses about 1,560 federal government employees on its 20 floors of office space. Each floor has an occupied area of 19,500 sq. ft (1927 m²). That makes the total occupied area in the building 390,000 sq. ft (36550 m²). The ground floor with the main lobby, and the basement floor with various service spaces, are not part of the pilot project. These floors are each served by a separate air handling unit independent of the office tower air handling systems.

On the office floors, the ceiling space is used as a return air plenum. The floor-to-ceiling height is, on average, about 11 feet.

The smallest workstation, which for air quality control purposes is called the critical workstation, is located in the interior zone, measures 150 sq ft (14 m²), and receives 90 cfm (42.5 L/s) of supply air for temperature control purposes.

There are approximately 600 critical workstations in the building. As already observed in the previous section, this variable has no effect on the outcome of the air quality control according to the revised ASHRAE Standard 62-1981R (ref. #5).

The building is served by three perimeter and four interior air handling units, see Figure 11. The perimeter units supply induction units on all office space floors through a system of risers which are feeding the air downward, from the top floor down to the second floor. The interior units each serve one half of the interior zones on either the 2nd to 11th floors or the 12th to 21st floors. For the air handling units distribution arrangement see Figure 12.

All seven air handling units take air from a common mixing chamber. They are all equipped with a free cooling cycle to provide cooling by outdoor air whenever the outdoor temperature falls below 54 deg F (12.2 deg C). The return air temperature in summer, that is when the air quality control is needed, is at 76 deg F (24.5 deg C), and the supply air leaves the cooling coil at 54 deg F (12.2 deg C). The outdoor air temperature, as established by ASHRAE for 1.5% design conditions, is -17 deg F (-27.2 deg C) in winter and 90 deg F (32.2 deg C) dry bulb and 72 deg F (22.2 deg C) wet bulb in summer. The expression of 1.5% design condition means that for no more than 1.5% of the total hours in one year, over the past ten years on average, has the actual temperature surpassed the design conditions. The CO₂ concentration outside the building is 340 ppm.

5.3 Steady State Calculations

Based on the above physical characteristics of the building, and operational characteristics of its air handling systems, the steady state CO₂ concentration for a minimum outdoor air per person of 20 cfm (10 L/s) is calculated. The calculation is performed by the previously described computer program called CO2S.BAS. User's instruction are in Appendix E. The resulting CO₂ concentration in steady state is 820 ppm and the minimum free cooling temperature is -79 deg F (-61.6 deg C).

The steady state CO₂ concentration is calculated by using the program's ventilation option 3 defined in section 2.7, which is based on the multi-zone ventilation equation 6-1 from ASHRAE Standard 62-1981R (ref. #5).

The program uses thermal properties of standard air only. That allows for calculation of the total minimum air quantity, based on the air temperatures, as a fraction of the total air supply:

$$\frac{\text{RAT} - \text{SAT}}{\text{RAT} - \text{OAT}} = \frac{76 - 54}{76 - (-79)} = 0.142 \quad (25)$$

where: RAT is the return air temperature, in deg F (deg C),
 SAT is the supply air temperature, in deg F (deg C),
 OAT is the outdoor air temperature, in deg F (deg C).

Note: The temperatures used in this calculation are taken from the specifications of the example building.

This translates into a 14.2% of total air supply, or a total outdoor air quantity of 34,325 cfm (16,160 L/s), or an average outdoor air of 21.95 cfm (10.4 L/s) per person.

5.4 Transient State Calculations

According to the formula for transient state calculation, the steady state CO₂ concentration is not completely reached within the eight or ten hours of normal operation on a regular weekday. The degree to which the formula represents the actual CO₂ concentration build up needs to be verified on site by a specially designed testing procedure described below in the article on commissioning.

For reasons of analysis needed for preparation of a ventilation control strategy, the transient state calculations are performed for the following three cases:

- Case 1: Full occupancy is accomplished instantaneously.
- Case 2: People entering the building in a steady stream to complete the full occupancy in 1 hour.
- Case 3: Same as case 2, except the occupancy is completed in 2 hours.

The resulting CO₂ concentration buildup curves are plotted in Fig 10 from calculation results shown in Table 14.

5.5 Control Strategy

The overall air quality control strategy must include two ventilation processes; it must have the most effective and energy efficient purging process of the building prior to occupancy hours, and it must ensure the most energy efficient compliance with the air quality standard during the occupancy hours. The following discussion leads to identification of a strategy that would ensure a compliance with the ventilation standard, that would be both energy efficient, and practical to implement.

Let us start with the latter process of compliance with the air quality standard, and then concentrate on the building purging process.

5.6 Ventilation During Occupancy Hours

In an attempt to make the air quality control strategy as simple as possible for both economic, and application reasons, it is suggested that the control set point be calculated as if the building were occupied as specified in Case 1. The calculated point would then be used for the modulation of outdoor air damper and relief air damper positions. That means that the dampers would open more if the measured CO_2 concentration rises above the calculated set point, and would close more if the measured concentration falls below the calculated set point. There are some problems with this simplification attempt, which are discussed and resolved below.

The occupancy profile is seldom as specified in case 1. It usually takes between one and two hours to reach a level of substantially completed occupancy.

If the above assumption is applied as stated, an error of under-ventilation will occur due the calculated point of CO_2 concentration being higher than would normally be expected, which would result in a drastic reduction of outdoor air supply until such time when all the people have arrived. Corrections would need to be made in order to eliminate the error of under-ventilation. Analysis summarized in Table 15 reveals that the correction could be achieved by a delay in the calculation of set point. If the occupancy is completed in two hours, then a delay of 32 minutes would be needed, if it takes 1 hour to fill the building, a delay of 16 minutes would do. See also Figure 13.

This is not an acceptable strategy, because it invites the possibility of producing significant errors of under-ventilation which could be noticeable by the occupants.

An improvement can be achieved by preparing a profile of occupancy buildup in certain small intervals, say 10 minutes each. The error of under-ventilation would be reduced to 6 minutes for an occupancy buildup of 2 hours and to about one minute if it takes 1 hour to complete the occupancy. See Figure 14.

This strategy is more acceptable, however, it still leaves room for human errors which could be made in day-to-day operation. The next strategy is based on a linear occupancy buildup. The built-in errors are further reduced relative to the previous strategy, and are related to the degree by which the actual occupancy buildup differs from the linear profile.

Theoretically, a perfect solution to the above problem could be reached by installing a counting device which would continuously report the number of people present in real time terms. The algorithm in the controller would then make corrections

to the calculated set point in real time terms. A solution which could come closest to this is derived from observation of curves in Figure 14. Closer observation shows that substantial parts of cases 2 and 3 curves are almost linear. That represents a constant increase in concentration with a constant increase in occupancy. The increase in concentration in cases 2 and 3 could be approximately represented by a straight line, the slope of which is equal to the increase of concentration in case 1 at a point in time which is equal approximately to $1/4$ of the time to the occurrence of the concentration increase in either of cases 2 or 3, see Figure 15. This approximation is used as a basis of the following control strategy which requires no interference by the property management team on a day-to-day basis.

5.6.1 Proposed Sequence of Operation.

1. Start to calculate the control set point from the transient state equation for full occupancy in accordance with the occupancy profile of case 1.
2. At the same time start measuring the CO_2 concentration in the return air stream.
3. Calculate the increase in measured concentration.
4. Compare the increase of measured concentration with the calculated set-point concentration increase at time of $t=t_1/4$.
5. If the measured concentration increase in the next moment starts to become higher than the concentration increase in case 1 in time of $t=t_1/4$, then the outdoor air damper and the relief air damper should be adjusted to allow more outdoor air in.
6. In case the increase of measured concentration starts to drop off, the dampers should not be adjusted to reduce the amount of outdoor air, but should rather wait in that position until the concentration increase due to the further increase in occupancy is equal to the concentration increase on the calculated set point curve of case 1 in a new point of time of $t=t_1/4$. If the concentration starts to decrease, the damper should move to reduce the outdoor air intake.
7. This process shall be repeated until the full occupancy is reached, at which time the actual measured concentration merges with the calculated set-point of case 1.

The above strategy promises to meet the above stated objectives for air quality control in an energy efficient manner as closely as possible. The assumptions on which the above strategy is based need to be verified by an extended commissioning process, which would be expected to answer whether the $t=t_1/4$ time is the most representative one, and whether the substitution of the case 2 and 3 curves by straight lines produces good results for a variable rate of occupancy increase within the occupancy buildup period.

One important point about the above control strategy should be made at this time. The strategy is not affected by a constant volume of outdoor air which is necessary to make up for the washroom exhaust, see Figure 16. As soon as enough people arrive to generate a rate of increase in measured concentration sufficient to comply with the condition on which the control strategy is based, the controller will start to modulate the relief air damper and start to open its outdoor air damper beyond the make up air position.

5.6.2 Impact of Variable Occupancy

In many cases it is not certain whether the full occupancy will be reached at all. This is especially true during the summer, when the mechanical cooling cycle is used, and when the minimum outdoor air control coincides with the vacation time.

An analysis of this situation reveals that the steady state CO_2 concentration requires only slight modification to the outdoor air supply per person for a great range of occupancy. Table 16 shows the effect of using the design occupancy of 1,560, with steady state CO_2 concentration of 820 ppm, on the actual occupancy of between 900 and 1,800 people.

Using the design occupancy of 1,560 could result in an under-ventilation of up to 5%, if the actual occupancy is lower than the design occupancy. Similarly, an over-ventilation may result for actual occupancy above the design count. To bring all the possible errors to the 'safe' side, it would suffice to change the design occupancy from 1,560 to 981. That would produce compliance with the ventilation standard for any occupancy count.

5.6.3 Conditions for Compliance with the Ventilation Standard

Let us now look into the idea of compliance with the ventilation standard from a different perspective than discussed above. From the point of the ventilation standard ASHRAE 61-1981R (ref. #5), which defines the comfort level of air quality on a long

term exposure basis, the daily compliance with the standard is what counts. This is analogous to the compliance with a ventilation standard which prescribes the health and safety levels of air quality. The correlation between comfort level and health and safety level is in many cases made arbitrarily. The comfort level is set as a fraction of the health and safety level. In some cases that fraction is 1/10, in other cases 1/2.

The health and safety standard usually lists two acceptable levels of air contaminant: a lower level for a long term exposure, which is an average concentration in an 8 hour day, and a 40 hour week; and a higher level for short term exposures, usually for 15 minutes a day.

With the corrections discussed above, or without them, the compliance of the long term comfort level criteria is always going to be achieved by the CO₂ method. The above efforts were made to obtain a CO₂ air quality control device which would give no reason whatsoever for questioning its ability to comply with the standard at all times in real time terms.

5.7 Pre-Occupancy Purging of the Building

The above text discussed the air quality control strategy for ventilation during the occupied hours only. Since in the building, there are also air pollutants that are generated continuously, even during the unoccupied hours, there is a need to dilute their concentration by a purging process before the time of occupancy.

The following text discusses the ventilation strategies for purging the buildings of their air contaminants in the most energy efficient manner.

5.7.1 The Purging Process

In an ideal situation, the dilution process follows the expression (ref. #7):

$$c = CI * \exp(-a*t) \quad (26)$$

where: CI = initial concentration of air contaminant,
c = final concentration of air contaminant,

- a = diluent air flow, free of the contaminant, in number of air changes per minute,
 t = time, in minutes, between occurrence of initial and final concentration, and
 e_e = 2.71828, the base of the natural logarithms

Based on this expression, assuming a perfect mixing of contaminated and diluent air, the dilution of the initial concentration can be calculated as

$$-(a*t) = \ln (C_i / c) \quad (27)$$

If a certain degree of dilution, is to be achieved in one hour on weekdays not following a weekend, then the same dilution will be achieved in 2.6 hours on a weekday after the two-day weekend, and in 2.9 hours on a weekday after a three-day weekend. This is based on an assumption that the out-gassing process increases the concentration of contaminant linearly, see Figure 17. In order to establish the purging strategy in a building, it is necessary to:

- a) identify the critical air contaminant,
- b) measure its generation rate,
- c) measure its concentration in the outdoor air, and know its acceptable comfort level for a long term occupancy.

For illustration purposes, let us assume that the required dilution can be achieved in the pilot project by two air changes of outdoor air. The washroom exhaust fan capacity represents 0.3 air changes per hour, the minimum outdoor air at full occupancy represents 0.5 air changes per hour, and the maximum achievable ventilation rate with 100% outdoor air taken into all air handling units represents 3.4 air changes per hour.

5.7.2 Strategy for the Mechanical Cooling Mode of Operation

Since the existing documentation is available in the British System of Units only, the following calculations are not performed nor translated into SI units. The design conditions for Ottawa in summer are, according to ASHRAE Handbook of Fundamen-

tals (ref. #1), 90 deg F dry bulb and 72 deg F wet bulb. These conditions are expected to be reached at 2 p.m., solar time. A Design Handbook by Carrier Air Conditioning Company (ref. #6), lists day time corrections for these conditions as follows.

For 8 a.m., the dry bulb temperature is corrected by -12 deg F and the wet bulb temperature by -3 deg F. Corrections for 6 a.m. are not listed, but can be extrapolated as -12 and -4 deg F respectively. That makes the summer design air conditions in Ottawa at 6 a.m. 75 deg F dry bulb and 68 deg F wet bulb. The enthalpy at these conditions is 32.4 btu per lb of dry air.

Air at this condition can be brought in unconditioned, just filtered, for as long as needed to complete the required two air changes. At that time, the supply of outdoor air shall stop, and the entire air volume of the building shall be cooled down to the design room conditions of 75 deg F dry bulb and 50% RH, or 63.6 deg F wet bulb, which corresponds an enthalpy of 28.9 btu per lb of dry air. See psychrometric chart on Figure 18.

This cooling task can not be accomplished without reheat. The house lighting system may be conveniently used for that. The total cooling task is:

$$\frac{FA * CH * (H2 - H1)}{CV * 12000} = \frac{390000 * 11 * (32.4 - 28.9)}{13.7 * 12000} \quad (28)$$

$$= 117.4 \text{ Ton (of refrigeration per day: 24 hrs)}$$

where: FA = occupied floor are in square feet
 CH = ceiling height in feet
 H1 = enthalpy of outdoor air
 H2 = enthalpy of room air
 CV = specific volume of room air
 12000 = conversion multiplier from btu/h to ton of refrigeration per day

The installed cooling capacity in all seven air handling systems for this pilot project is: (29)

$$\frac{WF * (T2 - T1) * 500}{12000} = \frac{2100 * (53 - 42) * 500}{12000} \quad (29)$$

$$= 962.5 \text{ Ton}$$

where: WF = chilled water flow in usgpm
 T2 = leaving chilled water temperature in degF
 T1 = entering chilled water temperature in degF
 500 = a product of a specific heat of water:
 1 btu/lb, specific weight of water: 8.33
 lb/usgal, and 60 minute in 1 hour.

The available cooling capacity is adequate. Therefore, the cooling task can be accomplished by recirculating all the air in the building once through the cooling coils in all seven air handling systems. The time needed is 17.6 minutes (60 minutes divided by 3.4 air changes per hour).

From the above calculation the following ventilation strategy for the pre-occupancy purging of the building can be formulated:

All seven air handling units shall be turned on to work in a 100% outdoor air mode at the following times:

On a weekday not following a weekend the start up time is 51.2 minutes prior the occupancy time. This is comprised of 17.6 min for cooling and $(2 * 17.6)$ for purging, minus a credit of 1.6 minutes for washroom exhaust make up during the cooling period.

On a weekday following a two-day weekend the start up time is 107.5 minutes prior the occupancy time. The purging time is 2.6 times as long as on a regular weekday.

On a weekday following a three-day weekend the start up time is 153.3 minutes prior the occupancy time. In this case the purging takes 2.9 times as long.

5.7.3 Strategy for Free Cooling Mode of Operation

The following ventilation strategy is applicable whenever the air handling units are operating in a free cooling mode. In the pilot project, that occurs whenever the outdoor temperature is at or below 54 deg F.

Let us now investigate the free cooling cycle in the pilot project. The changes of outdoor air per hour are related to the outdoor temperature by a hyperbolic expression, which is presented in a graphic form on Figure 19. See also Table 17. The air change curve is drawn from the results of the outdoor temperature analysis.

The maximum air change rate per hour is 3.4 at 54 deg F, and the minimum rate of 0.5 air changes per hour is reached at -79 deg F. Since the Ottawa winter design temperature is well above the minimum outdoor air temperature for free cooling, the pilot project will automatically receive adequate flow of outdoor air in the free cooling mode of operation.

To better understand the significance of the pre-occupancy purging in the free cooling mode of operation, let us look first into the ventilation process of diluting the concentration of air contaminants generated by the building materials and furniture.

On a weekday, the air handling systems must be operating during the occupied hours, which are 7:30 to 17:30. During that time the number of air changes will accumulate in relation to the outdoor temperature. The accumulated value will never be less than 7, but it can be as high as 34 air changes per day. Since the majority of operating hours are in the temperature band between 40 and 50 degrees, the free cooling cycle represents a significant contribution to the air quality issue. This makes the free cooling a very attractive feature for solving or avoiding air quality problems.

In the strategy for mechanical cooling mode of operation, we have made an assumption that for an adequate purging of air contaminants which accumulate over night, we need to bring in a diluent air in volume equivalent to two complete air changes. To apply the same assumption to the free cooling cycle, we can show that a constant start up time, 35 minutes prior to occupancy time is required. (60 minutes divided by 3.4 air changes per hour times two required air changes).

The air handling units are equipped with adequate heating capacity, therefore there is no problem with keeping the room temperature under control. If, however, the heating load at or below certain outdoor temperature may pose an unmanageably high peak load to the central heating plant, the purging period may be extended over a longer period of time by throttling down the outdoor air intake.

Again, the start up time for a weekday following a two-day weekend is 2.6 times as long, and for a weekday following a three-day weekend 2.9 times as long.

5.8 Commissioning

In this section, numbers used for air handling equipment apply specifically to the pilot project being discussed. The procedure outlined could be used more generally.

Before the pilot project is accepted, several tests must be successfully passed.

The first round of tests must be performed in the factory. This shall include a testing of all functions of the control algorithm, as well as testing of the sensor signals which must be correlated with the input-output signals of the controller.

After the installation, all related temperature and fire safety functions must be checked out before the control loop is tested for a proper modulation of outdoor air dampers, exhaust air dampers and return air dampers.

Once it has been demonstrated that all the related operational functions perform well, the correlation between CO₂ generation and outdoor air quantity, which is the main function of the controller, must be established. Since the published CO₂ generation rate has been established in relation to the metabolic rate in a laboratory, it would not be advisable to use people as CO₂ generation sources for this test. A controlled source of CO₂ needs to be used.

The correlation does not have to be established at the full occupancy level, but preferably at a level close to it. In the pilot project, the washroom exhaust fans are handling 21,500 cfm. If the exact flow of these exhaust fans is verified by measurement, then the exact outdoor air flow can also be established by opening the outdoor air damper into its minimum position. From this known outdoor air flow, the number of people satisfied with the ventilation performance can be calculated. By knowing the number of people satisfied, the controlled CO₂ generation rate can be found from the known CO₂ generation rate of 0.005 l/s per person performing a sedentary type of work, and the testing could proceed.

By releasing the controlled flow of CO₂ into the return air stream, a series of CO₂ concentration measurements can be taken, and a CO₂ concentration build up curve can be plotted. The discrepancy between the measured and the predicted CO₂ concentration build up curve can be rectified by adjusting the time constant in the control algorithm.

Once this testing is successfully completed, the control module must be adjusted to the occupancy pattern. It is necessary to establish by observation, as accurately as possible, the time at which the occupancy reaches a count of 981. At that time the control algorithm shall start counting the time of transient state, and the CO₂ control loop shall be activated. Prior to that time the CO₂ control device shall perform monitoring functions only.

Similarly, the time in the control algorithm shall be re-set after the lunch break. The point of time, when the occupancy reaches 981 needs to also be established, for the same reasons.

To provide more stability into the control loop, it is necessary to find an upper limit of the damper position which would limit the outdoor air supply without restricting the ability of the control loop to maintain the calculated set point concentration. The upper limit must be established during commissioning from observations of the damper position when the control is achieved. This upper limit feature is similar to the upper limit temperature control concept for temperature control in ventilation units used for make up air supply.

The above commissioning procedures should ensure a good performance of the CO₂ control device. These procedures will leave many questions unanswered for people with deeper interest in the air quality issue. The supplier, however, would not be able to provide these answers due to the limited scope of the pilot project and due to the limitation of technical expertise characteristic of the application engineering in the HVAC industry. The following section deals with some of the unanswered questions in more detail.

5.9 Summary

As demonstrated for the pilot project, the CO₂ method can be used to reliably ensure the compliance with the ventilation standard in an energy efficient manner. The application is based on an analysis of variable occupancy during occupied hours.

Several control strategies are evaluated, and only the most accurate one is selected. The selected strategy will meet the accuracy requirements of compliance with the ventilation standard in real time terms.

Besides the control strategy for occupancy hours, also discussed is the strategy for ventilation prior the occupancy hours. Different strategies are needed for the mechanical cooling mode of operation and for the free cooling modes of operation. The discussions lead to a conclusion that the free cooling cycle should be installed, where possible, for its superior performance in air quality control.

When completed, the pilot project needs to be evaluated. The evaluation should be based on an intensive commissioning phase. Commissioning procedures for verification of the performance of the CO₂ method are presented.

6.0 FURTHER RESEARCH AND DEVELOPMENT

6.1 Scope

The previous sections explain how the presented CO₂ method could be used for air quality control in office buildings, to comply with the ventilation standard. The method offers a significant step on the road to resolving the air quality issue.

As mentioned throughout the text, the method will allow for research and development in many areas to be performed more effectively:

- ventilation effectiveness in a workstation

- ventilation effectiveness in a building

- accuracy of CO₂ sensors

- accuracy of the CO₂ method

- average generation rates of CO₂ by people

- hourly profile of generation rates in office buildings

- control of other air contaminants by CO₂

- out-gassing rates of air contaminants from building materials, and furniture in relation to the time elapsed since installation

Implementation of the CO₂ method will result in a widely achieved compliance with the ventilation standard. That will present a good opportunity to again review ASHRAE's latest revision, ASHRAE 62-1981R.

It will also set the stage for the research of a psychological nature. It is important to establish comfort levels of various individual air contaminants, and their comfort levels when they are present in combination with other contaminants or other stress sources. It will also be important to see the impact of compliance with the ventilation standard on the perception of air quality. This kind of research is very difficult to conduct even with the physical components of air quality under control.

The users of the end-product of the property management team, that is, the client personnel, have difficulty in discriminating

the correct cause of their discomfort in a workstation. They seem to always pick the air quality first. The property management team as well as the building owners are reluctant to allow for this kind of research for fear of receiving a bad name for their buildings. That would drastically affect their chances to lease space in such labelled buildings, whether the label is justified or not.

Another difficulty with the psychological type of research is in the nature of the research itself. Performance indicators obtained through this kind of research are not objectively measurable. They are usually based on a percentage of the population which is fully satisfied with the indicator, a small part of the population marginally satisfied, and only a small residue of the sample dissatisfied. This type of expression of performance introduces several questions for which there is usually only a subjective answer. The questions will ask: how is the percentage of satisfaction calculated; is the percentage applicable to the same individuals of the sample all the time; is the satisfaction averaged out every moment or over an eight hour per day basis the same; is the dissatisfaction caused by the air at the work place or by the air in other indoor spaces in which the people of the sample spent more time than they do in the office?

6.2 Direction

Since the 1970s, the air quality issue has received a great deal of attention by the general public, by the elected representatives and by the media. Since that time, indoor air quality has improved in many office buildings where the asbestos insulation has been removed, in many building where the UFFI based insulation has been removed, and in many public spaces where smoking has been banned.

These activities have an impact on the approval of research resources. However, research associated with air quality is not seen as being as urgent as research related to the life threatening diseases. The air quality issue in office buildings is an issue of comfort. It would therefore not be realistic that this type of research will receive a great deal resources from the public purse.

This situation presents the greatest challenge to the management of research and development in this area. A research and development plan for air quality must include all participants who could generate valuable data about air quality on a day-to-day basis. For that purpose the proposed CO₂ method seem to be the right answer. The method could be used, not only to control

air quality in real time terms, but could also be used as a management information system for reporting to the property management team information about the ventilation performance in terms in which the accommodation agreement is written.

It is hoped that the pilot project will be approved for the above reasons, and that the CO₂ method could contribute to the solution of the air quality issue as expected.

REFERENCES:

1. ASHRAE Handbook of Fundamentals
2. ASHRAE Handbook of Systems
3. ASHRAE Standard 62-1973, Ventilation for Acceptable Indoor Air Quality
4. ASHRAE Standard 62-1981, Ventilation for Acceptable Indoor Air Quality
5. ASHRAE Standard 62-1981R, Ventilation for Acceptable Indoor Air quality
6. Carrier Air Conditioning Company, System Design Manual, Part 1, Loads
7. Supplement to the National Building Code of Canada 1985
8. ASTM Special Technical Publication 555, Instrumentation for Monitoring Air Quality

Table 1: Potential Error of the Controlled Variable with a ± 50 ppm Instrument.

CO ₂ Concentration at Sensor	Potential Error of Controlled Variable			
	(cfm)		(L/s)	
	Max	Min	Max	Min
400	416.7	-37.9	199.7	-17.9
450	37.9	-14.2	17.9	-6.7
500	14.2	-7.4	6.7	-3.5
550	7.4	-4.6	3.5	-2.2
600	4.6	-3.1	2.2	-1.5
650	3.1	-2.2	1.5	-1.0
700	2.2	-1.7	1.0	-0.8
750	1.7	-1.3	0.8	-0.6
800	1.3	-1.1	0.6	-0.5
850	1.1	-0.9	0.5	-0.4
900	0.9	-0.7	0.4	-0.3
950	0.7	-0.6	0.3	-0.3
1000	0.6	-0.5	0.3	-0.2

See section 3.3 for discussion.

Table 2: Sample Input to the Computer Program CO2S.BAS,

Occupied Area	100,000 sq ft
Ceiling Height	11 ft
Number of Workstations	500
People Present	500
Smallest Workstation Size	120 sq ft
Air Supply to the Smallest Workstation	90 cfm
Workstation in a Critical Zone	200
Outdoor Air Supply per Person	20 cfm
Total Air Supply	120,000 cfm
Free Cooling Cycle	Y (yes)
Return Air Temperature	75 deg F
Supply Air Temperature	55 deg F
Outdoor Air Temperature	90 deg F
Outdoor CO ₂ Concentration	340 ppm
Initial CO ₂ Concentration	340 ppm

Table 3: Menu of Variables to be Analyzed in the Computer Program CO2S.BAS.

Floor Area.....	1
Floor-to-Ceiling Height.....	2
Number of Workstations.....	3
People Present.....	4
Smallest Workstation Size.....	5
Air Supply to the Smallest Workstation.....	6
Outdoor Air Supply per Person.....	7
Total Air Supply.....	8
Return Air Temperature.....	9
Supply Air Temperature.....	10
Outdoor Air Temperature.....	11
Outdoor Concentration of CO ₂	12
Initial Indoor Concentration of CO ₂	13
Flexible Hours.....	14
Ventilation Options.....	15
Change in Metabolism.....	16
Workstations in Critical Zone.....	17
No Further Analysis Needed.....	20

Select any number from above

Table 4A: Impact of Prescribed Outdoor Air Quantity on CO₂ Concentration, Air Changes per Hour and Outdoor Air per Person (Average), Ventilation Option 1, (all other ventilation parameters as per Table 2).

Prescribed Outdoor Air per Person		CO ₂ Concentration at Steady State		Air Changes per Hour	Outdoor Air per Person (Average)	
(cfm)	(L/s)		(ppm)		(cfm)	(L/s)
5	2.4		2459	0.14	5	2.4
10	4.7		1399	0.27	10	4.7
15	7.1	*	1046	0.41	15	7.1
20	9.4		870	0.55	20	9.4

* Recommended upper limit of CO₂ concentration.

Table 4B: Impact of Prescribed Outdoor Air Quantity on CO₂ Concentration, Air Changes per Hour and Outdoor Air per Person (Average), Ventilation Option 2, (all other ventilation Parameters as per Table 2).

Prescribed Outdoor Air per Person (cfm)	CO ₂ Concentration at Steady State (L/s)	CO ₂ Concentration (ppm)	Air Changes per Hour	Outdoor Air per Person (Average) (cfm)	Outdoor Air per Person (Average) (L/s)
5	2.4	1134	0.36	13	6.1
6	2.8	* 1000	0.44	16	7.6
10	4.7	737	0.73	27	12.7
15	7.1	605	1.09	40	18.9
20	9.4	539	1.45	53	25.0

* Recommended upper limit of CO₂ concentration.

Table 4C: Impact of Prescribed Outdoor Air Quantity on CO₂ Concentration, Air Changes per Hour and Outdoor Air per Person (Average), Ventilation Option 3, (all other ventilation parameters as per Table 2).

Prescribed Outdoor Air per Person (cfm)	CO ₂ Concentration at Steady State (L/s)	CO ₂ Concentration (ppm)	Air Changes per Hour	Outdoor Air per Person (Average) (cfm)	Outdoor Air per Person (Average) (L/s)
5	2.4	2385	0.14	5	2.4
10	4.7	1326	0.29	11	5.2
15	7.1	* 973	0.46	17	8.0
20	9.4	796	0.63	23	10.9

* Recommended upper limit of CO₂ concentration.

Table 5: Variation of Air Changes per Hour Required with Increasing Floor Area, (all other ventilation parameters as per Table 2).

Floor Area		CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
(sq ft)	(m ²)			(cfm)	(L/s)
50,000	4645	796	1.27	23	10.9
60,000	5575	796	1.06	23	10.9
70,000	6505	796	0.90	23	10.9
80,000	7435	796	0.79	23	10.9
90,000	8365	796	0.70	23	10.9
100,000	9205	796	0.63	23	10.9
110,000	10225	796	0.58	23	10.9
120,000	11150	796	0.53	23	10.9
130,000	12080	796	0.49	23	10.9
140,000	13010	796	0.45	23	10.9
150,000	13940	796	0.42	23	10.9

This result is the same for all three ventilation options.

Table 6: Variations of Air Changes per Hour Required with Increasing Ceiling Height, (all other ventilation parameters as per Table 2).

Ceiling Height		CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
(ft)	m			(cfm)	(L/s)
9	2.75	796	0.77	23	10.9
9.5	2.9	796	0.73	23	10.9
10	3.05	796	0.70	23	10.9
10.5	3.2	796	0.66	23	10.9
11	3.35	796	0.63	23	10.9
11.5	3.5	796	0.61	23	10.9
12	3.65	796	0.58	23	10.9

This result is the same for all three ventilation options.

Table 7A: Variation of Air Changes per Hour with Variable Occupancy, Ventilation Option 1, (all other ventilation parameters as per Table 2).

People Present	CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
			(cfm)	(L/s)
50	870	0.05	20	9.4
100	870	0.11	20	9.4
150	870	0.16	20	9.4
200	870	0.22	20	9.4
250	870	0.27	20	9.4
300	870	0.33	20	9.4
350	870	0.38	20	9.4
400	870	0.44	20	9.4
450	870	0.49	20	9.4
500	870	0.55	20	9.4
550	870	0.60	20	9.4
600	870	0.65	20	9.4

Table 7B: Variation of CO₂ Concentration and Outdoor Air per Person with Variable Occupancy (Average), Ventilation Option 2, (all other ventilation parameters as per Table 2).

People Present	CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
			(cfm)	(L/s)
50	360	1.45	533	246.4
100	380	1.45	267	126.0
150	400	1.45	178	84.0
200	419	1.45	133	62.8
250	439	1.45	107	56.5
300	459	1.45	89	42.0
350	479	1.45	76	35.9
400	499	1.45	67	31.6
450	519	1.45	59	27.8
500	539	1.45	53	25.0
550	558	1.45	48	22.7
600	578	1.45	44	20.8

Table 7C: Variable Air Changes per Hour and Outdoor Air per Person with Variable Occupancy (Average), Ventilation Option 3, (all other ventilation parameters as per Table 2).

People Present	CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average) (cfm)	(L/s)
50	756	0.07	25	11.8
100	761	0.14	25	11.8
150	765	0.20	25	11.8
200	770	0.27	25	11.8
250	774	0.33	24	11.3
300	778	0.40	24	11.3
350	783	0.46	24	11.3
400	787	0.52	24	11.3
450	792	0.58	23	10.9
500	796	0.63	23	10.9
550	801	0.69	23	10.9
600	805	0.75	23	10.9

Table 8: Effect of Smallest Workstation Size on CO₂ Concentration, Air Changes per Hour and Outdoor Air per Person (Average), (all other ventilation parameters as per Table 2).

Workstation Size (sq ft)	m ²	CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average) (cfm)	(L/s)
100	9.3	796	0.63	23	10.9
110	10.2	796	0.63	23	10.9
120	11.2	796	0.63	23	10.9
130	12.1	796	0.63	23	10.9
140	13.0	796	0.63	23	10.9
150	13.9	796	0.63	23	10.9

This result is the same for all three ventilation options

Table 9: Effect of Air Supply Variation to the Smallest Workstation on CO_2 Concentration, Air Changes per Hour and Outdoor Air per Person (Average), (all other ventilation parameters as per Table 2).

Workstation Air Supply		CO ₂ Concentration at Steady State	Air Changes per Hour	Outdoor Air per Person (Average)	
(cfm)	(L/s)	(ppm)		(cfm)	(L/s)
60	28.3	796	0.63	23	10.9
70	33.0	796	0.63	23	10.9
80	37.8	796	0.63	23	10.9
90	42.5	796	0.63	23	10.9
100	47.2	796	0.63	23	10.9
110	51.9	796	0.63	23	10.9
120	56.6	796	0.63	23	10.9
130	61.4	796	0.63	23	10.9
140	66.1	796	0.63	23	10.9
150	70.8	796	0.63	23	10.9

The amount of workstation supply air has no effect on the CO_2 concentration, the air changes per hour nor the average outdoor air per person in any of the three ventilation options.

Table 10A: Effect of Total Air Supply Variation on CO_2 Concentration, Air Changes per Hour and Outdoor Air per Person (Average), Ventilation Option 1, (all other ventilation Parameters as per Table 2).

Total Air Supply		CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
(cfm)	(L/s)			(cfm)	(L/s)
50,000	23,600	870	0.55	20	9.4
60,000	28,320	870	0.55	20	9.4
70,000	33,040	870	0.55	20	9.4
80,000	37,760	870	0.55	20	9.4
90,000	42,480	870	0.55	20	9.4
100,000	47,200	870	0.55	20	9.4
110,000	51,920	870	0.55	20	9.4
120,000	56,640	870	0.55	20	9.4
130,000	61,360	870	0.55	20	9.4
140,000	66,080	870	0.55	20	9.4

Table 10B: Effect of Total Air Supply Variation on CO₂ Concentration, Air Changes per Hour and Outdoor Air per Person (Average), Ventilation Option 2, (all other ventilation parameters as per Table 2):

Total Air Supply		CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
(cfm)	(L/s)			(cfm)	(L/s)
50,000	32,600	817	0.61	22	10.4
60,000	28,320	737	0.73	27	12.7
70,000	33,040	680	0.85	31	14.6
80,000	37,760	638	0.97	36	17.0
90,000	42,480	605	1.09	40	18.9
100,000	47,200	578	1.21	44	20.8
110,000	51,920	557	1.33	49	23.1
120,000	56,640	539	1.45	53	25.0
130,000	61,360	523	1.58	58	27.4
140,000	66,080	510	1.70	62	29.3

Table 10C: Effect of Total Air Supply Variation on CO₂ Concentration, Air Changes per Hour and Outdoor Air per Person (Average), Ventilation Option 3, (all other ventilation parameters as per Table 2):

Total Air Supply		CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
(cfm)	(L/s)			(cfm)	(L/s)
50,000	23,600	858	0.56	20	9.4
60,000	28,320	840	0.58	21	9.9
70,000	33,040	828	0.59	22	10.4
80,000	37,760	818	0.60	22	10.4
90,000	42,480	811	0.61	22	10.4
100,000	47,200	805	0.62	23	10.9
110,000	51,920	800	0.63	23	10.9
120,000	56,640	796	0.63	23	10.9
130,000	61,360	793	0.64	23	10.9
140,000	66,080	790	0.64	24	11.3

Table 11A: Effect of Outdoor Air Temperature Variation on CO₂ Concentration, Air Changes per Hour and Outdoor Air per Person (Average), Ventilation Option 1, (all other ventilation parameters as per Table 2).

Outdoor Air Temp			CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
(deg F)	(deg C)				(cfm)	(L/s)
-25	-31.6		561	1.31	48	22.7
-15	-26.1		539	1.45	53	25.0
-5	-20.5		517	1.64	60	28.3
5	-15.0	Free	494	1.87	69	32.6
15	-9.4		472	2.18	80	37.8
25	-3.9	Cooling	450	2.62	96	45.3
35	1.7		428	3.27	120	56.6
45	7.2	↑	406	4.36	160	75.5
55	12.8		384	6.55	240	113.3
65	18.3		870	0.55	20	9.4

Table 11B: Effect of Outdoor Air Temperature Variation on CO₂ Concentration, Air Changes per Hour and Outdoor Air per Person (Average), Ventilation Option 2, (all other ventilation parameters as per Table 2).

Outdoor Air Temp			CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
(deg F)	(deg C)				(cfm)	(L/s)
-25	-31.6		539	1.45	53	25.0
-15	-26.1		539	1.45	53	25.0
-5	-20.5		517	1.64	60	28.3
5	-15.0	Free	494	1.87	69	32.6
15	-9.4		472	2.18	80	37.8
25	-3.9	Cooling	450	2.62	96	45.3
35	1.7		428	3.27	120	56.6
45	7.2	↑	406	4.36	160	75.5
55	12.8		384	6.55	240	113.3
65	18.3		539	1.45	53	9.4

Table 11C: Effect of Outdoor Air Temperature Variation on CO₂ Concentration, Air Changes per Hour and Outdoor per Person (Average), Ventilation Option 3, (all other ventilation parameters as per Table 2).

Outdoor Air Temp		CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average)	
(deg F)	(deg C)			(cfm)	(L/s)
-25	-31.6	561	1.31	48	22.7
-15	-26.1	539	1.45	53	25.0
-5	-20.5	517	1.64	60	28.3
5	-15.0	494	1.87	69	32.6
15	-9.4	472	2.18	80	37.8
25	-3.9	450	2.62	96	45.3
35	1.7	428	3.27	120	56.6
45	7.2	406	4.36	160	75.5
55	12.8	384	6.55	240	113.3
65	18.3	796	0.63	23	9.4

Table 12: Effect of Outdoor CO₂ Concentration on Indoor CO₂ Concentration.

Outdoor CO ₂ Concentration (ppm)	CO ₂ Concentration at Steady State (ppm)	Air Changes per Hour	Outdoor Air per Person (Average) (cfm)	(L/s)
300	756	0.63	23	10.9
310	766	0.63	23	10.9
320	776	0.63	23	10.9
330	786	0.63	23	10.9
340	796	0.63	23	10.9
350	806	0.63	23	10.9
360	816	0.63	23	10.9
370	826	0.63	23	10.9
380	836	0.63	23	10.9
390	846	0.63	23	10.9
400	856	0.63	23	10.9

The result is the same for all three ventilation options.

Table 13: CO₂ Concentration Buildup for Different Initial Concentration when all the People Enter Simultaneously
(All other ventilation parameters as per Table 2)

Elapsed Time (min)	Initial Concentration of CO ₂		
	340 ppm	400 ppm	500 ppm
1	344	403	503
2	348	407	505
3	351	410	508
4	355	413	510
5	359	417	513
6	363	420	515
7	366	423	517
8	370	426	520
9	373	429	522
10	377	432	525
15	394	448	536
20	411	462	547
25	427	476	558
30	443	490	568
35	457	503	578
40	472	515	588
45	485	527	597
50	499	539	606
55	511	550	614
60	523	560	622
70	546	580	637
80	567	599	652
90	587	616	665
100	605	632	677
110	621	646	688
120	637	660	698
130	651	672	707
140	664	683	716
150	767	694	724
160	687	704	731
170	697	713	738
180	707	721	744
210	731	742	761
240	750	759	773
270	765	772	783
300	777	782	791
330	786	790	797
360	793	797	802

Table 14: CO₂ Concentration Buildup with Initial Concentration of 340 ppm for Various Occupancy Buildup (All other ventilation parameters as per Table 2).

Elapsed Time (min)	Occupancy Buildup Time		
	0 min	60 min	120 min
1	344	340	340
2	348	340	340
3	351	340	340
4	355	341	340
5	359	341	341
6	363	342	341
7	366	343	341
8	370	344	342
9	373	345	342
10	377	346	343
15	394	353	346
20	411	363	351
25	427	375	358
30	443	390	365
35	457	408	374
40	472	427	383
45	485	448	394
50	499	472	405
55	511	497	418
60	523	523	431
70	546	546	459
80	567	567	491
90	587	587	525
100	605	605	561
110	621	621	598
120	637	637	637
130	651	651	651
140	664	664	664
150	676	676	676
160	687	687	687
170	697	697	697
180	707	707	707
210	731	731	731
240	750	750	750
270	765	765	765
300	777	777	777
330	786	786	786
360	793	793	793

Table 15: Corrections for Occupancy Buildup Error through Delays in Control Set Point Calculation.

At Times when Fraction of People Present is	Delay in Calculation of Control Set Point Occupancy Buildup in Minutes			
	Linear Increase		Step Function Increase	
	60	120	60	120
1/6	16	32	0	1.25
2/6	16	32	1.1	3.0
3/6	16	32	1.25	5.3
4/6	10	21	1.25	6.0
5/6	5	11	1.1	5.0
1	0	0	0	0

A graphical expression of the correction of errors for linear occupancy buildup in 120 minutes is shown in Figure 13. The above results indicate that the minimum delays are 26, 32, 1.25 and 6 minutes in the respective cases.

Table 16: Effect of Ventilation Calculated Set Point on Actual Ventilation.

People Present (PP)	CO ₂ Concentration at Steady State (ppm)	Actual Fraction of Ventilation if Set Point	
		820 ppm (1560PP)	795 ppm (981PP)
900	791	0.940	N/A
981	795	0.948	1.000
1000	796	0.950	1.002
1100	800	0.960	1.013
1200	804	0.966	1.019
1300	809	0.977	1.030
1400	813	0.985	1.039
1500	818	0.996	1.049
1560	820	1.000	1.055
1600	822	1.004	1.059

If ventilation set point is selected at 795 ppm of steady state concentration, which coincides with the outdoor air supply needed for washroom exhaust makeup, then the building will never be under ventilated. If the set point corresponds 1560 people present (820 ppm), then under-ventilation will occur when occupancy is between 981 and 1560 people.

Table 17: Effect of Free Cooling Mode of Operation on Ventilation Performance

Outdoor Air Temp		CO ₂ Concentration at Steady State	Air Changes per Hour	Outdoor Air per Person (Average)	Air
(deg F)	(deg C)	(ppm)		(cfm)	(L/s)
-26	-32.2	657	0.73	33	15.6
-16	-26.6	626	0.81	37	17.5
-6	-21.1	595	0.90	42	19.8
4	-15.6	563	1.03	47	22.2
14	-10.0	532	1.20	55	26.0
24	-4.4	501	1.43	66	31.2
34	1.1	470	1.77	81	38.2
44	6.7	439	2.33	107	50.5
54	12.2	408	3.38	155	73.2
64	17.8	820	0.48	22	10.4
74	23.3	820	0.48	22	10.4
84	28.9	820	0.48	22	10.4

FIGURE 1: SCHEMATIC DIAGRAM OF VENTILATION SYSTEM SERVING WORKSTATIONS IN AN OFFICE BUILDING

$$\text{Eq. 6-1: } V_{ot} / \sum V_{st} = [\sum V_{on} / \sum V_{st}] / [1 + \sum V_{on} / \sum V_{st} - V_{oc} / V_{sc}]$$

FIGURE 2: SCHEMATIC DIAGRAM TO ILLUSTRATE RELATIONSHIP OF TERMS IN VENTILATION OPTION 3 (ASHRAE 62 - 1981R)

FIGURE 3: POTENTIAL ERROR OF CONTROLLED VARIABLE (OUTDOOR AIR SUPPLY / PERSON) FOR A RANGE OF MEASURED CO₂ CONCENTRATIONS WITH A GIVEN INSTRUMENT HAVING ACCURACY OF CO₂ MEASURED OF ± 50 ppm.

FIGURE 4: POTENTIAL ERROR OF CONTROLLED VARIABLE (OUTDOOR AIR SUPPLY / PERSON) FOR A RANGE OF MEASURED CO₂ CONCENTRATIONS WITH A GIVEN INSTRUMENT HAVING ACCURACY OF CO₂ MEASURED OF ± 100 ppm.

FIGURE 5: RANGE OF POTENTIAL ERRORS WITH THREE TEMPERATURE MEASUREMENT POINTS, EACH HAVING $\pm 0.5^{\circ}\text{C}$ ACCURACY

FIGURE 6: RANGE OF POTENTIAL ERRORS IN OUTDOOR AIR QUANTITY WHEN THREE TEMPERATURES ARE USED TO DETERMINE OUTDOOR AIR QUANTITY FOR TEMPERATURES READING ACCURACY OF $\pm 0.5^{\circ}\text{C}$

FIGURE 7: LOCUS OF POTENTIAL ERRORS OF OUTDOOR AIR QUANTITY WITH CHANGING OUTDOOR AIR TEMPERATURE FOR A TEMPERATURE SENSOR OF $\pm 0.5^{\circ}\text{C}$ ACCURACY

WHERE

V = velocity

C = constant

h_{wi} = velocity
pressure

ρ_i = air density

$\pi = k \cdot L$

TEMPERATURE DEVIATION VELOCITY DEVIATION EFFECT

$$\bar{t} = \frac{1}{\pi} \sum_{i=1}^{\pi} t_i \quad v_i = C \sqrt{h_{wi} / \rho_i}$$

FIGURE 8: PROPOSED GRID OF MEASUREMENT POINTS ACROSS A DUCT TO OBTAIN AVERAGE TEMPERATURE AND VELOCITY IN A STRATIFIED FLOW

FIGURE 10. THREE DIFFERENT LOG OF CO₂ CONTROL SET POINT FOR THREE RATES OF OCCUPANCY BUILDUP.

SUPPLY AIR SYSTEM
 PERIMETER INDUCTION SYSTEM NORTH & WEST
 BUILDING ZONE NO. 1

FIGURE 11: ILLUSTRATION OF HVAC ZONES IN THE EXAMPLE BUILDING

FLOOR No.: FLOOR ELEVATION: FLOOR AREA: GROSS SQ. FT.		SCALE: FLOOR TO FLOOR HEIGHT.	
SCHEMATIC FLOOR PLAN		DATE	
JEANNE MANCE BUILDING TUNNEY'S PASTURE, OTTAWA, ONT.			SHEET

DESCRIPTION. BUILDING SUPPLY, RETURN & EXHAUST ZONES 1-7.

REMARKS

FIGURE 12: SUPPLY AND RETURN AIR SCHEMATIC DIAGRAM

SYSTEM SCHEMATIC

DATE

JEANNE MANCE BUILDING
TUNNEY'S PASTURE, OTTAWA, ONT.

SHEET :

87077-3

FIGURE 13: LOCUS OF CONTROL SET POINT DELAYS USED TO COMPENSATE FOR LINEAR OCCUPANCY BUILD UP, REFER TO TABLE 15

FIGURE 14: CO₂ CONCENTRATION ERRORS WHEN THE OCCUPANTS ENTERED IN A STEP FUNCTION FASHION

FIGURE 15: ILLUSTRATION OF PROPOSED CONTROL STRATEGY

FIGURE 16: REQUIRED OUTDOOR AIR FOR THREE OCCUPANCY CASES

FIGURE 17: LOCUS OF AIR CONTAMINANT CONCENTRATION WITH INTERMITTENT OPERATION OF HVAC SYSTEMS (OFF DURING SILENT HOURS)

2 of/de 2

MICRO

ASHRAE PSYCHROMETRIC CHART NO. 1

NORMAL TEMPERATURE

BAROMETRIC PRESSURE 29.921 INCHES OF MERCURY

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SEA LEVEL

FIGURE 18: COLLING LOAD AFTER THE PRE-OCCUPANCY PURGING OF THE BUILDING

FIGURE 19: OUTDOOR AIR CHANGES AT VARIABLE OUTDOOR AIR TEMPERATURE IN A FREE COOLING MODE OF OPERATION

APPENDIX A

Derivation of Ventilation Option 3

The latest revision of ventilation standard, ASHRAE 62-1981R, introduces a new way of calculating the total amount of outdoor air needed for a multi-zone ventilation arrangement in which the outdoor air intake is controlled by one mixing chamber. See Equation 3 in Section 2 of the main text, and see also Figure 3. In the following calculations, all the critical workstations are represented by one critical zone, and all the other workstations are represented by one non-critical zone.

For purposes of this derivation, equation 1 from page 8 of the main text can be translated into terms consistent with equation 3 as follows:

$$V_{en} = OAS * PP \quad (29)$$

where: V_{en} = total outdoor air required by ventilation option 1
 OAS = required outdoor air supply per person
 PP = people present

Similarly, equation 2 from page 9 can be translated as follows:

$$TOA = V_{sc} * \frac{V_{oc}}{V_{sc}} \quad (30)$$

where: TOA = total outdoor air required by ventilation option 2
 V_{sc} = total supply air
 V_{oc} = outdoor air required in a critical zone
 V_{sc} = supply air required in a critical zone

The difference between the outdoor air requirement in ventilation option 2 and ventilation option 1 can be calculated from the following:

$$V_{era} = V_{sc} * \frac{V_{oc}}{V_{sc}} - V_{en} \quad (31)$$

where: V_{ora} = the amount of outdoor air beyond the outdoor air requirement by ventilation option 1.

If it could be physically arranged for the amount of outdoor air equal to V_{ora} to by-pass the ventilated space, while the V_{en} amount of outdoor air would go into the space to mix with CO_2 generated by the PP people, then the concentration of return air coming from the ventilated space may be obtained as follows:

$$(CLVCZ - CLOA) = \frac{Q_g * PP}{V_{en}} \quad (32)$$

where: $CLVCZ$ = CO_2 concentration in the ventilated space
 $CLOA$ = CO_2 concentration in the outdoor air
 Q_g = CO_2 generation rate by a person

After the return air from the ventilated space mixes with the by-passed outdoor air V_{ora} , the resulting return air concentration will be reduced according the law of conservation of mass as follows:

$$(CLVRA - CLOA) * V_{ret} = (CLVCZ - CLOA) * (V_{ret} - V_{ora}) \quad (33)$$

which could be rearranged into:

$$(CLVRA - CLOA) = (CLVCZ - CLOA) * \frac{V_{ret} - V_{ora}}{V_{ret}} \quad (34)$$

where: $CLVRA$ = the CO_2 concentration in return air after the mixing took place

The return air is partly exhausted and partly replaced by outdoor air. The amount of outdoor air needed to produce the desired concentration of return from the ventilated space which would in turn produce the desired concentration in the mixed return air can be calculated as follows:

$$(CLVRA - CLOA) = \frac{Q_g * PP}{V_{ret}} \quad (35)$$

Above equations 32, 34, and 35 combined together result in the following expression:

$$\frac{Q_a * PP}{V_{ot}} = \frac{Q_a * PP}{V_{on}} * \frac{V_{ot} - V_{ora}}{V_{ot}} \quad (36)$$

By manipulation of this equation, and by substitution for V_{ora} from equation 31, the following expression can be obtained:

$$\frac{V_{ot}}{V_{ot}} = \frac{V_{ot} + V_{on} - V_{ot} * (V_{ora}/V_{ot})}{V_{on}} \quad (37)$$

Further manipulation leads to the last expression which resembles equation 6 from the ASHRAE Standard 62-1981R (ref. #5).

$$\frac{V_{ot}}{V_{ot}} = \frac{V_{on}/V_{ot}}{1 + V_{on}/V_{ot} - V_{ora}/V_{ot}} \quad (36)$$

APPENDIX B

Flow Diagram of Computer Program CO2S.BAS.

APPENDIX C

LISTING OF COMPUTER PROGRAM CO2S.BAS

```

10 CLS
20 FOR X=1 TO 79
30 PRINT "*";
40 NEXT X
50 PRINT:PRINT:PRINT:PRINT:PRINT
60 PRINT TAB(20)"AIR QUALITY CONTROL IN OFFICE BUILDINGS"
70 PRINT:PRINT
80 PRINT TAB(30) "BY A CO2 METHOD"
90 PRINT:PRINT:PRINT:PRINT:PRINT:PRINT
100 PRINT "PREPARED BY:"
110 PRINT:PRINT "F. VACULIK,"
120 PRINT "PUBLIC WORKS CANADA";TAB(60)"JANUARY 1987"
130 PRINT:PRINT
140 FOR X=1 TO 79
150 PRINT "*";
160 NEXT X
170 PRINT
230 PRINT
240 INPUT "Ready (press ENTER key)";I
250 CLS
260 PRINT "DISCLAIMER"
270 PRINT
280 PRINT
290 PRINT "THE USER OF THE COMPUTER PROGRAM SHALL DO SO ENTIRELY AT HIS, HER OR
ITS OWN"
300 PRINT "RISK AND HER MAJESTY SHALL NOT BE LIABLE TO THE USER FOR ANY DAMAGE OR
R LOSS"
310 PRINT "WHATSOEVER, INCLUDING LOSS OF PROFIT, LOSS OF SAVINGS OR OTHER INCIDE
NTAL OR"
320 PRINT "CONSEQUENTIAL LOSS, THAT MAY BE SUSTAINED BY THE USER ARISING OUT OF
THE USE"
330 PRINT "OF OR INABILITY TO USE COMPUTER PROGRAM OR FROM ANY OTHER CAUSE WHATS
OEVER"
332 PRINT "AND REGARDLESS OF WHETHER OR NOT ANY LOSS OR DAMAGE SHALL BE CAUSED-B
Y OR BE"
334 PRINT "DUE TO THE NEGLIGENCE OF HER MAJESTY, HER AGENTS, SERVANTS OR EMPLOYE
ES,"
336 PRINT "OR ANY, SOME OR ALL OF THEM, OR OTHERWISE HOWSOEVER."
340 PRINT:PRINT:PRINT:PRINT:PRINT:PRINT
380 PRINT "NOTE:"TAB(7)"THIS PROGRAM IS FOR INTERNAL USE ONLY! DO NOT MAKE COPIE
S."
390 PRINT:PRINT
450 INPUT "Ready (press ENTER key)";I

```

```

900 CLS
905 PRINT " The total outdoor air is calculated in this program from the informat
ion"
907 PRINT " in ASHRAE Standard 62-1981 either: "
910 PRINT:PRINT "*" as a product of the minimum outdoor air per person"
912 PRINT " and the number of people present.....OPTI
ON 1"
914 PRINT:PRINT "*" or from the percentage of outdoor air in supply"
916 PRINT " air in the critical workstation or zone.....OPTI
ON 2"
918 PRINT:PRINT "*" or from the mixing formula for a multi-zone"
919 PRINT " application - Equation 6-1, ASHRAE Standard 62-1981a....OPTI
ON 3"
920 PRINT:PRINT
930 PRINT:PRINT "SELECT OPTIONS:..... (previously selected option)";
EO
960 PRINT:PRINT:INPUT " INPUT..... 1, 2 or 3":EO
970 IF EO <> 1 AND EO <> 2 AND EO <> 3 GOTO 930
980 PRINT:PRINT
982 IF N=15 GOTO 1900
990 CLS
1000 REM***** INPUTS *****
1010 INPUT "Floor area served by the A/H unit in sqft" "; TFA
1020 PRINT
1030 INPUT "Floor-to-ceiling height in ft" "; H
1040 PRINT
1050 INPUT "How many workstations" "; WS
1060 PRINT
1070 INPUT "How many people are present" "; PP
1080 PRINT
1090 INPUT "What is the smallest workstation size in sq ft" "; SFA
1100 PRINT
1110 INPUT "Air supply to the smallest workstation" "; AS
1112 PRINT
1114 INPUT "Workstations in critical zone" "; WSCZ
1118 PFC=WSCZ
1120 PRINT
1124 CZAS=AS*PFC
1130 INPUT "Minimum outdoor air supply in cfm per person" "; OAS
1140 PRINT
1150 INPUT "Total air supply by the A/H unit in cfm" "; TAS
1160 PRINT
1170 PRINT "Select the predominant activity"
1180 PRINT:PRINT"Reclining, at rest.....1"
1190 PRINT "Sedentary, at ease (office work).....2"
1200 PRINT "Standing, bench work.....3"
1210 PRINT
1220 INPUT " "; MA
1230 IF MA = 1 THEN COR = .0036: GOTO 1265
1240 IF MA = 2 THEN COR = .005: GOTO 1265
1250 IF MA = 3 THEN COR = .0072: GOTO 1265

```

```

1260 GOTO 1170
1265 IF N=16 GOTO 1900
1270 PRINT:PRINT "The CO2 generation rate is "COR "1/s per person."
1272 PRINT:INPUT "Do you want to change any of the above      y/n";I$
1274 IF I$= "n" GOTO 1278
1275 IF I$= "N" GOTO 1278
1276 IF I$= "y" GOTO 990
1277 IF I$= "Y" GOTO 990 ELSE GOTO 1272
1278 CLS
1280 PRINT:INPUT "Free cooling cycle                        y/n      ";FC$
1300 IF FC$="y" AND FC$="Y" AND FC$="n" AND FC$="N" GOTO 1280
1310 PRINT
1320 INPUT "Return air temperature in deg F              "; RAT
1330 PRINT
1340 INPUT "Supply air temperature in deg F              "; LAT
1350 PRINT
1360 INPUT "Outdoor air temperature in deg F             "; OAT
1370 PRINT
1380 INPUT "Outdoor concentration of CO2 in ppm          "; CE
1390 PRINT
1400 INPUT "Initial indoor concentration of CO2 in ppm   "; CO
1410 PRINT
1412 PRINT:INPUT "Do you want to change any of the above      y/n";I$
1414 IF I$= "n" GOTO 1900
1415 IF I$= "N" GOTO 1900
1416 IF I$= "y" GOTO 1280
1417 IF I$= "Y" GOTO 1280 ELSE GOTO 1412
1900 REM *****  OUTPUTS  *****
1902 GOSUB 6050
1910 PRINT
1920 REM *****INPUT PRINTOUT *****
1930 CLS
1932 PRINT TAB(16) "SUMMARY"
1934 PRINT:PRINT
1940 PRINT "Floor area served by the A/H unit              "TFA" sqft"
1950 PRINT "Floor-to-ceiling height                            "H  " ft
1960 PRINT "Number of workstations                             "WS
1970 PRINT "People present                                       "PP
1980 PRINT "The smallest workstation size                       "SFA" sqft"
1990 PRINT "Air supply to the smallest workstation              "AS"  cfm"
1992 PRINT "Workstations in critical zone                       "WSCZ
1994 PRINT "People in critical zone                             "PPC
1996 PRINT "Air supply to the critical zone                     "CZAS" cfm"
2000 PRINT "Minimum outdoor air supply per person              "OAS" cfm"
2010 PRINT "Total air supply by the A/H unit                   "TAS" cfm"
2020 PRINT "Return air temperature                             "RAT" deg F"
2030 PRINT "Supply air temperature                             "LAT" deg F"
2040 PRINT "Outdoor air temperature                             "OAT" deg F"
2050 PRINT "Outdoor CO2 concentration                           "CE" ppm"

```

```

2060 PRINT "Initial indoor CO2 concentration"           "CO" ppm"
2070 PRINT "Steady state CO2 concentration"           "CD" ppm"
2080 PRINT "Minimum free cooling temperature"          "CINT(OATM)"deg F"
2082 PRINT:INPUT "To continue, press the ENTER key";I$
2092 PRINT:INPUT "CO2 concentration profile.....y/n";I$
2094 IF I$="n" GOTO 2400
2095 IF I$="N" GOTO 2400
2096 IF I$="y" GOTO 2200
2097 IF I$="Y" GOTO 2200 ELSE GOTO 2092
2100 CLS
2200 REM ***** BUILT UP CURVE *****
2202 PRINT:PRINT
2210 PRINT TAB(7)"ELAPSED TIME";TAB(34)"CO2 CONCENTRATION"
2220 PRINT:PRINT
2230 FOR T=1 TO 10 STEP 1
2240 GOSUB 6500
2250 NEXT T
2260 FOR T=15 TO 60 STEP 5
2270 GOSUB 6500
2280 NEXT T
2282 INPUT I$
2290 FOR T=70 TO 180 STEP 10
2300 GOSUB 6500
2310 NEXT T
2320 FOR T=210 TO 480 STEP 30
2322 GOSUB 6500
2330 NEXT T
2335 INPUT I$
2400 REM *****SENSIBILITY OF THE VARIABLES *****
2420 CLS
2450 PRINT "Which variable shall be analyzed"
2470 PRINT
2540 PRINT "Floor area.....1"
2550 PRINT "Floor-to-ceiling height.....2"
2560 PRINT "Number of workstations.....3"
2570 PRINT "People present.....4"
2580 PRINT "Smallest workstation size.....5"
2590 PRINT "Air supply to the smallest workstation.....6"
2600 PRINT "Outdoor air supply per person.....7"
2610 PRINT "Total air supply.....8"
2620 PRINT "Return air temperature .....9"
2630 PRINT "Supply air temperature.....10"
2640 PRINT "Outdoor air temperature .....11"
2650 PRINT "Outdoor concentration of CO2.....12"
2660 PRINT "Initial indoor concentration of CO2 .....13"
2661 PRINT "Flexible hours.....14"
2662 PRINT "Ventilation options.....15"
2665 PRINT "Change in metabolism.....16"
2666 PRINT "Workstations in critical zone.....17"
2668 PRINT "No further analysis needed.....20"
2669 PRINT:INPUT "Select any number from above ";N

```

```

2670 IF N=1 GOTO 2900
2680 IF N=2 GOTO 3100
2690 IF N=3 GOTO 3300
2700 IF N=4 GOTO 3500
2710 IF N=5 GOTO 3700
2720 IF N=6 GOTO 3900
2730 IF N=7 GOTO 4100
2740 IF N=8 GOTO 4300
2750 IF N=9 GOTO 4500
2760 IF N=10 GOTO 4700
2770 IF N=11 GOTO 4900
2772 IF N=12 GOTO 5100
2774 IF N=13 GOTO 5300
2776 IF N=14 GOTO 5500
2780 IF N=15 GOTO 5700
2782 IF N=16 GOTO 1160
2784 IF N=17 GOTO 7500
2790 IF N=20 THEN END
2800 IF N=1 AND N=2 AND N=3 AND N=4 AND N=5 AND N=6 AND N=7 AND N=8 AND
NK>9 AND N=10 AND N=11 AND N=12 AND N=13 AND N=14 AND N=15 AND N=16 AND
NK>17 AND N=18 AND N=20 GOTO 2666
2900 REM ***** FLOOR AREA *****
2910 PRINT:PRINT
2920 PRINT "FLOOR AREA"
2930 PRINT:PRINT
2940 PRINT "FLOOR AREA";TAB(22)"CO2 CONCENTRATION";TAB(44)"AIR CHANGES";TAB(60)"
OUTDOOR AIR RATE"
2945 PRINT "SOFT";TAB(22)"ppm";TAB(44)"PER HOUR";TAB(60)"PER PERSON"
2950 PRINT:INPUT "Low limit " ;LL
2960 INPUT "Hi limit " ;HL
2962 IF HL<LL GOTO 2960
2970 INPUT "Step " ;ST:PRINT
2980 FOR TFA=LL TO HL STEP ST
2990 GOSUB 6050
2992 GOSUB 7100
3000 PRINT TAB(3) TFA;TAB(28) CD;TAB(49) A;TAB(70) CINT(CD/PP)
3010 NEXT TFA
3020 PRINT:INPUT "Input the initial or new value";TFA
3030 GOTO 1900
3100 REM ***** CEILING HEIGHT *****
3110 PRINT:PRINT
3120 PRINT "CEILING HEIGHT"
3130 PRINT:PRINT
3140 PRINT "CEILING HEIGHT";TAB(22)"CO2 CONCENTRATION";TAB(44)"AIR CHANGES";TAB(
60) "OUTDOOR AIR RATE"
3145 PRINT "FT";TAB(22)"ppm";TAB(44)"PER HOUR";TAB(60)"PER PERSON"
3150 PRINT:INPUT "Low limit " ;LL

```

```

3160 INPUT "Hi limit"           ";HL
3162 IF HL<LL GOTO 3160
3170 INPUT "Step"              ";ST:PRINT
3180 FOR H=LL TO HL STEP ST
3190 GOSUB 6050
3192 GOSUB 7100
3200 PRINT TAB(3) H;TAB(28) CD; TAB(49) A;TAB(70) CINT(OD/PP)
3210 NEXT H
3220 PRINT:INPUT "Input the initial or new value";H
3230 GOTO 1900
3300 REM ***** WORKSTATIONS *****
3310 PRINT:PRINT
3320 PRINT "WORKSTATIONS"
3330 PRINT:PRINT
3340 PRINT "WORKSTATIONS"; TAB(22) "CO2 CONCENTRATION"; TAB(44) "AIR CHANGES";TA
B(60) "OUTDOOR AIR RATE"
3345 PRINT TAB(22)"ppm";TAB(44)"PER HOUR";TAB(60)"PER PERSON"
3350 PRINT:INPUT "Low limit"           ";LL
3360 INPUT "Hi limit"           ";HL
3362 IF HL<LL GOTO 3360
3370 INPUT "Step"              ";ST:PRINT
3380 FOR WS=LL TO HL STEP ST
3390 GOSUB 6050
3392 GOSUB 7100
3400 PRINT TAB(3) WS;TAB(28) CD; TAB(49) A;TAB(70) CINT(OD/PP)
3410 NEXT WS
3420 PRINT:INPUT "Input the initial or new value";WS
3430 GOTO 1900
3500 REM ***** PEOPLE PRESENT *****
3510 PRINT:PRINT
3520 PRINT "PEOPLE PRESENT"
3530 PRINT:PRINT
3540 PRINT "PEOPLE PRESENT"; TAB(22) "CO2 CONCENTRATION"; TAB(44) "AIR CHANGES";
TAB(60) "OUTDOOR AIR RATE"
3545 PRINT TAB(22)"ppm";TAB(44)"PER HOUR";TAB(60)"PER PERSON"
3550 PRINT:INPUT "Low limit"           ";LL
3560 INPUT "Hi limit"           ";HL
3562 IF HL<LL GOTO 3560
3570 INPUT "Step"              ";ST:PRINT
3580 FOR PP=LL TO HL STEP ST
3590 GOSUB 6050
3592 GOSUB 7100
3600 PRINT TAB(3) PP;TAB(28) CD; TAB(49) A;TAB(70) CINT(OD/PP)
3610 NEXT PP
3620 PRINT:INPUT "Input the initial or new value";PP
3630 GOTO 1900

```



```

3700 REM ***** SMALLEST WORKSTATION *****
3710 PRINT:PRINT
3720 PRINT "SMALLEST WORKSTATION SIZE"
3730 PRINT:PRINT
3740 PRINT "WORKSTATION SIZE";TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGES" ;
TAB(60) "OUTDOOR AIR RATE"
3745 PRINT "SQFT";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
3750 PRINT:INPUT "Low limit " ";LL
3760 INPUT "Hi limit " ";HL
3762 IF HL<LL GOTO 3760
3770 INPUT "Step " ";ST:PRINT
3780 FOR SFA=LL TO HL STEP ST
3790 GOSUB 6050
3792 GOSUB 7100
3800 PRINT TAB(3) SFA;TAB(28) CD TAB(49) A;TAB(70) CINT(CD/PP)
3810 NEXT SFA
3820 PRINT:INPUT "Input the initial or new value";SFA
3830 GOTO 1900
3900 REM ***** WORKSTATION AIR SUPPLY *****
3910 PRINT:PRINT
3920 PRINT "WORKSTATION AIR SUPPLY"
3930 PRINT:PRINT
3940 PRINT "WORKST'N AIR SUPPLY"; TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGE
S";TAB(60) "OUTDOOR AIR RATE"
3945 PRINT "cfm";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
3950 PRINT:INPUT "Low limit " ";LL
3960 INPUT "Hi limit " ";HL
3962 IF HL<LL GOTO 3960
3970 INPUT "Step " ";ST:PRINT
3980 FOR AS=LL TO HL STEP ST
3990 GOSUB 6050
3992 GOSUB 7100
4000 PRINT TAB(3) AS;TAB(28) CD; TAB(49) A;TAB(70) CINT(CD/PP)
4010 NEXT AS
4020 PRINT:INPUT "Input the initial or new value";AS
4030 GOTO 1900
4100 REM ***** OUTDOOR AIR *****
4110 PRINT:PRINT
4120 PRINT "OUTDOOR AIR"
4130 PRINT:PRINT
4140 PRINT "OUTDOOR AIR";TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGES" ;TAB(6
0) "OUTDOOR AIR RATE"
4145 PRINT "CFM";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
4150 PRINT:INPUT "Low limit " ";LL
4155 INPUT "Hi limit " ";HL
4162 IF HL<LL GOTO 4160
4170 INPUT "Step " ";ST:PRINT
4180 FOR OAS=LL TO HL STEP ST
4190 GOSUB 6050
4192 GOSUB 7100
4200 PRINT TAB(3) OAS;TAB(28) CD TAB(49) A;TAB(70) CINT(CD/PP)

```

```

4210 NEXT OAS
4220 PRINT:INPUT "Input the initial or new value":OAS
4230 GOTO 1900
4300 REM ***** AIR SUPPLY *****
4310 PRINT:PRINT
4320 PRINT "AIR SUPPLY"
4330 PRINT:PRINT
4340 PRINT "AIR SUPPLY";TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGES" ;TAB(60
) "OUTDOOR AIR RATE"
4345 PRINT "CFM";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
4350 PRINT:INPUT "Low limit " ;LL
4360 INPUT "Hi limit " ;HL
4362 IF HL<LL GOTO 4360
4370 INPUT "Step " ;ST:PRINT
4380 FOR TAS=LL TO HL STEP ST
4390 GOSUB 6050
4392 GOSUB 7100
4400 PRINT TAB(3) TAS;TAB(28) CD TAB(49) A;TAB(70) CINT(OD/FF)
4410 NEXT TAS
4420 PRINT:INPUT "Input the initial or new value":TAS
4430 GOTO 1900
4500 REM ***** RETURN AIR TEMP *****
4520 PRINT "RETURN AIR TEMP"
4530 PRINT:PRINT
4540 PRINT "RETURN AIR TEMP";TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGES" ;T
AB(60) "OUTDOOR AIR RATE"
4545 PRINT "deg F";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
4550 PRINT:INPUT "Low limit " ;LL
4560 INPUT "Hi limit " ;HL
4562 IF HL<LL GOTO 4560
4570 INPUT "Step " ;ST:PRINT
4580 FOR RAT=LL TO HL STEP ST
4590 GOSUB 6050
4592 GOSUB 7100
4600 PRINT TAB(3) RAT;TAB(28) CD TAB(49) A;TAB(70) CINT(OD/FF)
4610 NEXT RAT
4620 PRINT:INPUT "Input the initial or new value":RAT
4630 GOTO 1900
4700 REM ***** SUPPLY AIR TEMP *****
4720 PRINT "SUPPLY AIR TEMP"
4730 PRINT:PRINT
4740 PRINT "SUPPLY AIR TEMP";TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGES" ;T
AB(60) "OUTDOOR AIR RATE"
4745 PRINT "deg F";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
4750 PRINT:INPUT "Low limit " ;LL
4760 INPUT "Hi limit " ;HL
4762 IF HL<LL GOTO 4760
4770 INPUT "Step " ;ST:PRINT
4780 FOR LAT=LL TO HL STEP ST
4790 GOSUB 6050

```

```

4792 GOSUB 7100
4800 PRINT TAB(3) LAT;TAB(28) CD TAB(49) A;TAB(70) CINT(CD/PP)
4810 NEXT LAT
4820 PRINT:INPUT "Input the initial or new value";LAT
4830 GOTO 1900
4900 REM ***** OUTDOOR AIR TEMP *****
4920 PRINT "OUTDOOR AIR TEMP"
4930 PRINT:PRINT
4940 PRINT "OUTDOOR AIR TEMP";TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGES" ;
TAB(60) "OUTDOOR AIR RATE"
4945 PRINT "deg F";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
4950 PRINT:INPUT "Low limit" ";LL
4960 INPUT "Hi limit" ";HL
4962 IF HL<LL GOTO 4960
4970 INPUT "Step" ";ST:PRINT
4980 FOR DAT=LL TO HL STEP ST
4990 GOSUB 6050
4992 GOSUB 7100
5000 PRINT TAB(3) DAT;TAB(28) CD TAB(49) A;TAB(70) CINT(CD/PP)
5010 NEXT DAT
5020 PRINT:INPUT "Input the initial or new value";DAT
5030 GOTO 1900
5100 REM ***** OUTDOOR CO2 *****
5120 PRINT "OUTDOOR CO2"
5130 PRINT:PRINT
5140 PRINT "OUTDOOR CO2";TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGES" ;TAB(60) "OUTDOOR AIR RATE"
5145 PRINT "ppm";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
5150 PRINT:INPUT "Low limit" ";LL
5160 INPUT "Hi limit" ";HL
5162 IF HL<LL GOTO 5160
5170 INPUT "Step" ";ST:PRINT
5180 FOR CE=LL TO HL STEP ST
5190 GOSUB 6050
5192 GOSUB 7100
5200 PRINT TAB(3) CE;TAB(28) CD TAB(49) A;TAB(70) CINT(CD/PP)
5210 NEXT CE
5220 PRINT:INPUT "Input the initial or new value";CE
5230 GOTO 1900
5300 REM ***** INITIAL CO2 *****
5320 PRINT "INITIAL CO2"
5330 PRINT:PRINT
5340 PRINT "INITIAL CO2";TAB(22) "CO2 CONCENTRATION";TAB(44) "AIR CHANGES" ;TAB(60) "OUTDOOR AIR RATE"
5345 PRINT "ppm";TAB(22) "ppm";TAB(44) "PER HOUR";TAB(60) "PER PERSON"
5350 PRINT:INPUT "Low limit" ";LL
5360 INPUT "Hi limit" ";HL
5362 IF HL<LL GOTO 5360
5370 INPUT "Step" ";ST:PRINT
5380 FOR CO=LL TO HL STEP ST

```

```

5390 GOSUB 6050
5392 GOSUB 7100
5400 PRINT TAB(3) CD: TAB(28) CD TAB(49) A: TAB(70) CINT(OD/PP)
5410 NEXT CD
5420 PRINT: INPUT "Input the initial or new value": CD
5430 GOTO 1900
5500 REM ***** FLEXIBLE HOURS *****
5502 PRINT: PRINT
5504 PRINT "FLEXIBLE HOURS
5506 PRINT: PRINT
5510 INPUT "At what minute people start coming in" "; T1
5520 INPUT "At what minute they are all in" "; T2
5522 PRINT TAB(7) "ELAPSED TIME"; TAB(34) "CO2 CONCENTRATION"
5524 PRINT: PRINT
5530 FOR T=1 TO 10 STEP 1
5540 GOSUB 6600
5550 NEXT T
5560 FOR T=15 TO 60 STEP 5
5570 GOSUB 6600
5580 NEXT T
5582 INPUT I#
5590 FOR T=70 TO 180 STEP 10
5600 GOSUB 6600
5610 NEXT T
5620 FOR T=210 TO 480 STEP 30
5622 GOSUB 6600
5630 NEXT T
5635 INPUT I#
5650 GOTO 1900
6000 REM ***** OUTPUTS *****
6050 REM ***** CALCULATIONS *****
6060 AWS=TFA/WS
6080 AASS=TAS/WS
6100 ASFF=TAS/PP
6120 MPOA=OAS/AS
6122 IF EQ=2 GOTO 6140
6124 IF EQ=3 GOTO 6160
6130 QDM=OAS*PP
6132 GOTO 6170
6140 QDM=MPOA*TAS
6150 GOTO 6170
6160 UFOA=(OAS*PP)/TAS
6162 CFOA=(OAS*PPC)/CZAS
6164 QDM=(TAS*UFOA)/(1+UFOA-CFOA)
6170 QDMAX=TAS
6172 IF FC$="n" OR FC$="N" THEN QDMAX=QDM
6180 AASS=TAS/WS
6190 AMAX=(QDMAX*60)/(H*TFA)
6210 AMIN=(QDM*60)/(H*TFA)
6230 A=AMAX*(RAT-LAT)/(RAT-OAT)

```

```

6235 IF A<AMIN THEN A=AMIN
6250 OATM=RAT-(AMAX/AMIN)*(RAT-LAT)
6255 IF OAT>LAT THEN A=AMIN
6257 IF OAT=RAT THEN GOTO 6270
6260 QD=QDMAX*(RAT-LAT)/(RAT-OAT)
6270 IF FC$="n" OR FC$="N" THEN QDMAX= QDM
6280 IF OAT>LAT THEN QD=QDM
6290 IF OATM>OAT THEN QD=QDM
6300 I=1
6310 CI=(PF*COR*2.1186*1000000*I)/QD
6330 CD=CE+CI
6342 CD=CINT(CD)
6360 CC=(CD-CO)/CI
6380 C=CD-CI*CC*2.71828 (-A*T/60)
6390 C=CINT(C)
6400 RETURN
6500 REM ***** CO2 BUILD UP CURVE *****
6510 C=CD-CI*CC*2.71828 (-A*T/60)
6520 C=CINT(C)
6530 PRINT TAB(10)I;TAB(40)C
6540 RETURN
6600 REM ***** FLEXIBLE HOURS *****
6660 AWS=TFA/WS
6680 AASS=TAS/WS
6700 ASPP=TAS/PP
6720 MFOA=OAS/AS
6722 IF EQ=2 GOTO 6740
6724 IF EQ=3 GOTO 6760
6730 QDM=OAS*PP
6732 GOTO 6770
6740 QDM=MFOA*TAS
6750 GOTO 6770
6760 UFOA=(OAS*PP)/TAS
6762 CFOA=(OAS*PPC)/CZAS
6764 QDM=(TAS*UFOA)/(1+UFOA-CFOA)
6770 QDMAX=TAS
6772 IF FC$="n" OR FC$="N" THEN QDMAX= QDM
6790 AMAX=(QDMAX*60)/(H*TFA)
6810 AMIN=(QDM*60)/(H*TFA)
6830 A=AMAX*(RAT-LAT)/(RAT-OAT)
6835 IF A<AMIN THEN A=AMIN
6850 OATM=RAT-(AMAX/AMIN)*(RAT-LAT)
6855 IF OAT>LAT THEN A=AMIN
6857 IF OAT=RAT THEN GOTO 6870
6860 QD=QDMAX*(RAT-LAT)/(RAT-OAT)
6870 IF FC$="n" OR FC$="N" THEN QDMAX= QDM
6880 IF OAT>LAT THEN QD=QDM
6890 IF OATM>OAT THEN QD=QDM

```

```

6910 P=PP*(T-T1)/(T2-T1)
6912 IF P>PP THEN P=PP
6920 CI=(P*COR*2.1186*1000000*F)/QD
6930 CD=CE+CI
6940 CD=CINT(CD)
6950 CC=(CD-CD)/CI
6960 C=CD-CI*CC*2.71828 (-A*T/60)
6970 C=CINT(C)
6980 PRINT TAB(10)T;TAB(40)C
6990 RETURN
7100 REM ***** SUBROUTINE CHOP *****
7110 TEMP=A
7120 TEMP=100*TEMP
7130 TEMP=CINT(TEMP)
7140 TEMP=TEMP/100
7150 A=TEMP
7160 RETURN
7178 INPUT I
7500 REM ***** WORK STATIONS IN CRITICAL ZONE *****
7510 PRINT:PRINT
7520 PRINT "WORK STATIONS IN CRITICAL ZONE"
7530 PRINT:PRINT
7540 PRINT "WORK STATIONS"; TAB(22) "CO2 CONCENTRATION"; TAB(44) "AIR CHANGES"; TAB(65) "OUTDOOR AIR RATE"
7545 PRINT TAB(22)"ppm";TAB(44)"PER HOUR";TAB(65)"PER PERSON"
7550 PRINT:INPUT "Low limit " " ";LL
7560 INPUT "Hi limit " " ";HL
7562 IF HL<LL GOTO 7560
7570 INPUT "Step " " ";S1:PRINT
7580 FOR WSCZ=LL TO HL STEP S1
7590 GOSUB 6050
7592 GOSUB 7100
7600 PRINT TAB(3) WSCZ;TAB(28) CD; TAB(49) A;TAB(70) CINT(CD/PP)
7610 NEXT WSCZ
7620 INPUT "Input the initial value";WSCZ
7630 GOTO 1900

```

APPENDIX D

USERS INSTRUCTIONS FOR COMPUTER PROGRAM CO2S.BAS

These instruction are written for a user who is familiar enough with a personal computer to be able to turn it on, boot it with a DOS program, which should be at least of 2.1 version, and bring it to the operating mode in BASIC language.

Having done that, the user should insert the attached disc into drive B on a PC with two disc drives, or into drive A on a PC with a hard disc.

Then, by pressing the function key F3, the user should respond to the prompt of: "LOAD", by entering B: or A:, depending on the drive into which the disc has been inserted, followed by the name of the program, CO2S.BAS.

Once this is inputted, the Enter key shall be pressed. That will copy the program into the computer memory, and the user is ready to start with the program by pressing the function key F2.

Following that, the front page of the program will appear on the screen. To proceed, the user should keep pressing the Enter key until a decision about ventilation options needs to be made.

Selected should be number 3, followed by pressing the Enter key.

Next, the user is asked to enter all the physical and operational characteristics of the building. Each entry must be followed by pressing the Enter key. An example of these inputs is in Section 4.0 and in Table 2.

When asked to select the predominant activity, number 2 should be inputted, followed by pressing the Enter key.

If any of the above input needs to be modified (inputted again correctly), the user should press y or Y key, otherwise the n or N key should be pressed to continue.

The next question is about the cooling cycle. The answer should be y or Y for yes.

Next, the remaining operational characteristics from the example should be inputted. Again, if the input needs to be modified, the y or Y key should be pressed, otherwise the n or N key will cause the program to continue.

Next, the summary screen will appear. At this time, the user may wish to make a hard copy of the inputted variable. That is done by pressing and holding the Shift key while pressing

the PrtSc key. The information on the screen will be printed as displayed, providing the printer is ready.

After that, the Enter key should be pressed to continue. The next question is whether to calculate or skip the CO₂ concentration profile. If y or Y is entered, the CO₂ concentration for minutes 1 to 60 will appear on the screen. Then, by pressing the Enter key, the remainder of the profile is displayed, until minute 480.

If a hard copy is needed of any part of the CO₂ concentration profile, the print screen routine described above should be repeated.

By pressing the Enter key again, a screen with the menu of analytical options will appear.

The following procedure is similar for most of the variables. The analysis of three variables not fitting into the following routine, flexible hours, ventilation options and metabolic rate, is mentioned in the text. The prompts are self-explanatory, therefore no additional explanation is needed.

If variable 1, Floor Area, is to be analyzed, then number 1 should be entered, followed by pressing the enter key.

The low limit should be entered as 50000. The user should be careful not to press the enter key before entering a positive number for the low limit. The high limit should be entered as 150000, and the steps should be made at 10000. After pressing the enter key, the program will calculate and display for each step within the selected interval values of three ventilation indicators: The CO₂ concentration in steady state, the outdoor air changes per hour and the average outdoor air supply per person.

To go back to the summary screen, the user should enter first the initial or new value, entered should be 100000 followed by pressing the Enter key. That would bring the summary screen into the same set of variables as initially inputted.

Analyses of other variables, except for the three mentioned above, is similar in its procedure. Several examples of such analyses are shown in Appendix B. Also some additional instructions could be found in sections 4.0 and 5.0.

APPENDIX E

LISTING OF COMPUTER PROGRAM ERROR.BAS

```

10 CLS
20 PRINT:PRINT
30 PRINT "ERROR ANALYSIS OF OUTDOOR AIR SUPPLY"
40 PRINT
50 PRINT "This program is designed to analyse output errors of a CO2 sensor when
used for control of the outdoor air supply. To use the program it is necessary t
o know the following:"
60 PRINT
70 PRINT TAB(10)* accuracy of CO2 instruments,"
80 PRINT TAB(10)* outdoor concentration of CO2 and"
90 PRINT TAB(10)* CO2 concentration at the sensor in steady state."
100 PRINT:PRINT
110 PRINT "GOOD LUCK!"
120 PRINT:PRINT
130 PRINT TAB(50) "Program prepared by:"
140 PRINT:PRINT TAB(50) "Frank Vaculik"
150 PRINT TAB(50) "Facilities Operation"
160 PRINT TAB(50) "and Maintenance"
170 PRINT "November 1986"; TAB(50) "Public Works Canada"
220 PRINT:PRINT:INPUT "PRESS THE ENTER KEY WHEN READY";X
230 CLS
400 REM ERROR ANALYSIS
410 PRINT:PRINT
420 PRINT TAB(10) "E R R O R   A N A L Y S I S"
430 PRINT:PRINT
500 REM OUTDOOR AIR SENSOR
510 PRINT:INPUT "OUTDOOR AIR SENSOR .....Y/N "; A$
520 IF A$="N" GOTO 600
530 IF A$="Y" THEN PRINT:INPUT "INSTRUMENT ACCURACY plus/minus ppm";DCL0A
560 IF A$="Y" GOTO 600
570 PRINT "TRY AGAIN (IN UPPER CASE)";GOTO 500
600 REM ROOM AIR SENSOR
610 PRINT:INPUT "ROOM AIR SENSOR .....Y/N"; A$
620 IF A$="N" GOTO 700
630 IF A$="Y" THEN PRINT:INPUT "INSTRUMENT ACCURACY plus/minus ppm"; DCLV
660 IF A$="Y" GOTO 900
670 PRINT "TRY AGAIN";GOTO 600
700 REM RETURN AIR SENSOR
710 PRINT:INPUT "RETURN AIR SENSOR.....Y/N"; A$
720 IF A$="N" GOTO 800
730 IF A$="Y" THEN PRINT:INPUT "INSTRUMENT ACCURACY plus/minus ppm"; DCLV
760 IF A$="Y" GOTO 900
770 PRINT "TRY AGAIN";GOTO 700

```

```

800 REM SUPPLY AIR SENSOR
810 PRINT:INPUT "SUPPLY AIR SENSOR.....Y/N"; A$
820 IF A$="N" GOTO 900
830 IF A$="Y" THEN PRINT:INPUT "INSTRUMENT ACCURACY plus/minus ppm";DCLV
860 IF A$="Y" GOTO 900
870 PRINT "TRY AGAIN":GOTO 800
900 PRINT:INPUT "DO YOU WANT TO CHANGE THE ABOVE INPUT.....Y/N"; A$
910 IF A$="N" GOTO 940
920 IF A$="Y" GOTO 500
930 PRINT "TRY AGAIN": GOTO 900
940 PRINT "ACCURACY OF OUTDOOR SENSOR..... plus/minus"DCLV"ppm"
950 PRINT "ACCURACY OF INDOOR SENSOR.....plus/minus"DCLV"ppm"
1000 REM CO2 CONCENTRATION
1010 PRINT:INPUT "CO2 CONCENTRATION OUTDOORS.....ppm";CLOA
1020 PRINT
1040 PRINT
1100 REM OUTPUT
1160 PRINT
1170 PRINT "Select predominant activity"
1180 PRINT:PRINT"Reclining, at rest.....1"
1190 PRINT "Sedentary, at ease (office work).....2"
1200 PRINT "Standing, bench work.....3"
1210 PRINT
1220 INPUT " " "A
1230 IF A =1 THEN OG= .0036:GOTO 1270
1240 IF A=2 THEN OG=5.000001E-03:GOTO 1270
1250 IF A=3 THEN OG=.0072:GOTO 1270
1260 GOTO 1170
1270 PRINT:PRINT"The CO2 generation rate is "OG "1/s per person"
1280 PRINT:INPUT "Do you want to change any of the above Y/N";I$
1290 IF I$="N" GOTO 1340
1300 IF I$="Y" GOTO 1000
1310 PRINT "TRY AGAIN":GOTO 1280
1340 PRINT "CO2 OUTDOORS....."CLOA" ppm"
1350 PRINT:PRINT:PRINT
1355 K=1
1357 B=0
1360 REM CALCULATIONS
1370 PRINT "RANGE OF CO2 CONCENTRATION INDOORS"
1380 PRINT:PRINT
1390 INPUT "LOW LIMIT "LL
1392 LA=LL-(DCLV+CLOA+DCLV)
1394 IF LA>0 GOTO 1400
1396 PRINT:PRINT "TOO LOW, INCREASE BY AT LEAST "10+ABS(LA)" ppm"
1398 GOTO 1390
1400 INPUT "HIGH LIMIT "HL
1410 INPUT "STEP "ST
1412 PRINT:INPUT "DO YOU WANT TO CHANGE THE ABOVE INPUT.....Y/N"; A$
1414 IF A$="N" GOTO 1420
1416 IF A$="Y" GOTO 1370
1418 PRINT "TRY AGAIN": GOTO 1412
1420 FOR CLV= LL TO HL STEP ST
1435 IF B>0 GOTO 2000

```

```

1500 REM PRINTOUT
1505 PRINT:PRINT:PRINT
1507 GOSUB 2700
1510 PRINT"CO2"; TAB(40) "OUTPUT ERROR"
1520 PRINT "CONCENTRATION";TAB(28) "ABSOLUTE (cfm)";TAB(60)"RELATIVE (%)"
1540 PRINT "AT SENSOR";TAB(25) "MAX";TAB(40) "MIN";TAB(55) "MAX";TAB(70) "MIN"
1550 GOSUB 2700
1580 PRINT
2000 REM SUBROUTINE DQD
2010 QD=(QG*1000000*F)/(CLV-CLOA)
2030 QDMAX=(QG*1000000*F)/(CLV-DCLV-CLOA-DCLOA)
2040 QDMIN=(QG*1000000*F)/(CLV+DCLV-CLOA+DCLOA)
2045 IF AO$="N" GOTO 2120
2050 DQDF=(QDMAX-QD)/(2.5)
2060 DQDM=(QDMIN-QD)/(2.5)
2080 GOTO 2200
2120 DQDF=(QDMAX-QD)
2130 DQDM=(QDMIN-QD)
2200 PDQDF=((QD+DQDF)*100)/QD
2210 PDQDM=((QD+DQDM)*100)/QD
2260 TEMP= DQDF
2270 GOSUB 2800
2280 DQDF=TEMP
2290 TEMP=DQDM
2300 GOSUB 2800
2310 DQDM=TEMP
2320 TEMP=PDQDF
2330 GOSUB 2800
2340 PDQDF=TEMP
2350 TEMP=PDQDM
2360 GOSUB 2800
2370 PDQDM=TEMP
2390 PRINT CLV;TAB(25) DQDF;TAB(40) DQDM;TAB(55) PDQDF;TAB(70) PDQDM
2395 B=B+1
2400 NEXT CLV
2410 PRINT
2430 GOSUB 2700
2450 STOP
2700 REM line
2710 FOR N=1 TO 79
2720 PRINT "-";
2740 NEXT N
2750 RETURN
2800 REM SUBROUTINE CHOP
2810 TEMP=10*TEMP
2820 TEMP=CINT(TEMP)
2830 TEMP= TEMP/10
2840 RETURN

```

APPENDIX F

Specification Guide for CO₂ Meters

CO₂ meters shall be of a non-dispersive infrared absorption type with a 0 to 1000 ppm CO₂ scale and a 0 to 100 mV DC output. Their accuracy shall be 5% of the full scale.

CO₂ meters shall be calibrated at zero by a CO₂ gas and in their measuring span by a CO₂+N₂ gas. Both calibration gases shall be available from the supplier in ready-to-use portable containers.

CO₂ meters shall perform in a 0 to 40 deg C and 0 to 90% RH environment.

CO₂ meters and their calibration accessories shall be CSA approved.

Acceptable models: ACME CO₂ Monitor (patent pending),
FUJI 2FP5, and
Horiba APBA-210.

END

22-06-88

FIN