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INDOOR AIR QUALITY ASSESSMENT IN NON-INDUSTRIAL BUILDINGS

C.Y. Shaw
Institute of Research in Construction
National Research Council Canada, Ottawa

ABSTRACT - Common symptoms and causes of the Tight Building Syndrome are reviewed and a plan for assessing the air quality of non-industrial buildings is described. The proposed plan is intended for use by an investigation team typically consisting of an engineer and a technician with a strong background in HVAC systems, two or three part-time members familiar with standard industrial hygiene evaluation techniques, and several helpers. It has been applied to an eight-storey office building with nine air-conditioning systems. Methods of assessing the performance of HVAC systems and the feasibility of using carbon dioxide as an air quality index are discussed.

RÉSUMÉ - L'auteur examine les symptômes courants et les causes du "syndrome des immeubles étanches" et il décrit un plan d'évaluation de la qualité de l'air dans les bâtiments non industriels. Le plan en question est destiné à être utilisé par une équipe d'étude formée normalement d'un ingénieur et d'un technicien possédant une bonne connaissance des systèmes de CVC, de deux ou trois travailleurs à temps partiel connaissant les techniques standard d'évaluation en matière d'hygiène industrielle, et de plusieurs assistants. Le plan a été appliqué à un immeuble à bureaux de huit étages doté de neuf systèmes de conditionnement d'air. L'auteur étudie les méthodes d'évaluation de la performance des systèmes de CVC et la possibilité de se servir du gaz carbonique comme indice de la qualité de l'air.

INTRODUCTION

As concern for air quality in non-industrial buildings such as office buildings has grown, so too has the demand for services to assess it. The task is a difficult one, however, because the symptoms reported by office staff are too often diverse and non-specific. The work is further complicated by the fact that the established evaluation criteria for assessing exposure of industrial workers are not generally applicable to office environments; examples include the Permissible Exposure Limits (PELs) of the Occupational Safety and Health Administration (NIOSH), the Threshold Limit Values (TLVs) of the American Conference of Governmental Industrial Hygienists (ACGIH) and the Recommended Exposure Limits (RELs) of the National Institute for Occupational Safety and Health.

Although the ASHRAE standard[1] and similar standards provide guidelines for outdoor air requirements and exposure limits for office buildings, the information is far from complete. As a result, attempts to identify the sources of indoor air quality problems by means of standard industrial hygiene evaluation techniques may not always be successful.[2,3] Until better exposure limits and measurement techniques can be established, improved ventilation and removal of sources of contamination may be the best approach.

This paper presents a brief review of air quality related complaints frequently reported by office staff and describes a plan of investigation for an eight-storey office complex. The methods of assessing the performance of the HVAC systems and the feasibility of using carbon dioxide as an air quality index are discussed.

AIR QUALITY RELATED COMPLAINTS AND POSSIBLE CAUSES

The majority of air quality complaints are related to the Tight Building Syndrome, or Sick Building Syndrome. As defined by ACGIH, this describes a constellation of mucous membrane irritations, headache, and fatigue that may be caused by indoor air contaminants present at low levels, including tobacco smoke.[4] The most common symptoms, as identified by the World Health Organization, include:[5]

1. eye, nose, and throat irritation,
2. sensation of dry mucous membrane and skin,
3. erythema,
4. mental fatigue,
5. headaches, high frequency of airway infections and cough,
6. hoarseness, wheezing, itching, and unspecific hypersensitivity,
7. nausea and dizziness.

Some researchers have also identified the following common characteristics:[6,7]

1. Nonspecific symptoms that often resemble those of a common cold or a respiratory ailment.
2. Severity of the complaint increases as the day progresses. Complaints disappear when the individual leaves the building, i.e., evenings and weekends. As well, the complaint is not usually reflected in any increase in absence.
3. Affected buildings are usually energy-efficient, fairly new in design and construction, or recently refurbished.
4. Workers have little or no control over regulation of temperature, humidity, and lighting.

Several causes have been postulated for the Tight Building Syndrome, but none has been implicated convincingly as the definitive cause.[7,8] Postulated causes include inadequate ventilation, air that is too warm, too cold, too dry or too humid, noise, lighting, formaldehyde and other volatile organic compounds, micro-organisms, excess of air-borne particles, and work stress.[3,7,8]

PROPOSED PLAN

The proposed plan outlines the tasks required to assess the air quality of non-industrial buildings.[9] The objectives and details of each task will be discussed.

Task 1. Gathering Information

Task 1 is to understand the building itself, its surroundings and the concerns of the occupants about their environment. It calls for a thorough review of occupant concerns and a study of the building drawings, with particular attention to the HVAC systems. An occupant survey using, for example, the NIOSH Indoor Air Quality Questionnaire[2] can be conducted. Lacking proper data on the nature of the complaints, it is often difficult to define the types and extent of physical measurements necessary to reduce the uncertainty of the final recommendations.

Task 2. Walk-through Inspection

This task is to obtain additional information about the building and its environment. Efforts should be made to identify all potential sources of air contamination (e.g., combustion devices, copying machines, storage rooms and contents, and open drains). The project team should also look for common signs of problem HVAC systems (e.g., unintentionally closed outdoor air supply dampers and covered supply-air registers) and the factors that can adversely affect the performance of such systems (e.g., full-height partitions, and improperly located thermostats and outdoor air intakes).

During the visit, temperature, relative humidity and the degree of thermal comfort should be measured at several locations, including the problem areas. Concentrations of CO_2, CO and other contaminants may be measured as well. In addition, smoke pencils may be used to trace the air flow patterns and detect possible short circuiting between supply and return air flows. It is suggested that smoke pencil tests be conducted after regular working hours since some people are sensitive to the smoke.

Task 3. Initial Review

The objective of this task is to analyse the information obtained in Tasks 1 and 2 so as to develop a sampling and measurement strategy for an in-depth study, if necessary. An in-depth investigation should include Tasks 4 to 9.

Task 4. Measurement of Air Change Rates

Task 4 is to develop a suitable tracer gas sampling system for use with the tracer gas decay technique for measuring air change rates. The tracer gas decay technique involves injection of a small amount of a tracer gas, SF_6, into the building and measurement of the tracer gas concentrations with time. For buildings of complex shape, the samples taken from one or two locations per floor may not be sufficient to provide a good average tracer gas concentration of the whole building because of inadequate mixing. Thus, in the first few tests, additional samples should be taken from the floor space to ensure that the data from all sampling locations give similar air change rates. If this is not so, floor fans can be used to improve air mixing or additional sampling locations should be added.

One way to check the adequacy of a building's ventilation air is to ensure that its minimum air change rate meets the ventilation requirement recommended by prevailing standards such as ASHRAE 62-81R.[1] The minimum air change rate of a building can be determined by conducting four or five tracer gas decay tests under warm weather and calm wind conditions (to minimize air infiltration), setting the outdoor air dampers at the minimum position.

Task 5. Measurement of Air Distribution and Thermal Comfort

Task 5 is to collect information in addition to air change rates for assessing the performance of HVAC systems. It involves measurement of air temperatures, relative humidity and the degree of thermal comfort[10] in several locations, including problem areas, perimeter offices and internal rooms. The degree of thermal comfort gives an indication of the level of the occupants' satisfaction with the environment with respect to air temperature, relative humidity, air velocity, and the mean radiant temperature.

Tracer gas is also used to determine whether exhaust air re-enters the building and how fast a contaminant (or the outdoor air) spreads from its source (point of entry) to other areas. The re-entrainment of exhaust air can be detected by injecting a small amount of tracer gas into an exhaust system and measuring the concentrations at the outdoor air intake of each HVAC system. If tracer gas is detected, the outlet of the test exhaust system may have to be modified or relocated. This test should be conducted under various wind directions.

Contaminant dispersion rates can be determined by injecting a small amount of tracer gas at one location and measuring the concentrations with time at the injection location and at several other locations on each floor. The faster the concentrations in various areas approach that of the injection location, the higher the dispersion rate.

In general, for areas with known contaminant sources (e.g., a designated smoking room) the dispersion rate should be as low as possible to prevent the contaminated air from exhausting to the surrounding rooms. On the other hand, for general offices the dispersion rate should be as high as possible to facilitate a uniform distribution of outdoor air.

Task 6. Identification and Measurement of Contaminants

The objective of this task is to identify the major contaminants in the building and their sources, and to measure the concentrations. This can be achieved by analysing air (and water) samples collected from several locations inside and outside, particularly inside various compartments of the HVAC systems. Some of these measurements may have to be repeated at another season to detect seasonal pollutants. The protocols for conducting these measurements will be published separately.

Task 7. Interim Review

Task 7 is to identify the contaminants whose concentrations should be maintained below a certain level recommended by prevailing standards. It should also enable the project team to determine whether other specialists are needed to assist in the investigation.

Task 8. Establishment Of Relation Between Contaminant Concentrations and Air Change Rates

The objective of this task is to establish the relation between concentrations and air change rates for selected chemical and biological contaminants. These and established standards such as the ASHRAE 62-81R[1] can be used to determine the amount of outdoor air required to maintain the contaminants below prescribed limits if source removal is not practical. As well, it can be used to estimate the amount of outdoor air required to cope with any changes in certain contamination loads.

The relation between concentration and air change rate for each contaminant can be obtained by measuring continuously for one week the concentration and the actual air change rate. This should be repeated for four different outdoor air supply rates (actual air change rate includes the outdoor air supply rate and air infiltration rate). For this series of tests the normal operating schedule of the HVAC systems should not be changed, except that Saturday is treated as a weekday to determine the occupants' effect on the contaminant level. A minimum of one week's monitoring period for each air change rate is suggested because the weekly variation of some of the hard to control variables (e.g., floor cleaning schedule and use of copying machines) would be much less than the daily variation.

Task 9. Final Review and Task 10 Report

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

The report should give a brief description of the building, the nature of occupants' complaints, and the methods of measurement used. The results should be interpreted and presented in a manner easily understood by non-technical persons. Finally, the basis for the recommended remedial measures should also be stated.

APPLICATION OF THE PLAN

The proposed plan has been applied to a fully air-conditioned eight-storey library/office building in which the first four floors are office floors and the remaining four house library stacks. The floor area of the lower three floors is about 4800 m^2 each, and that of the upper five floors is about 2400 m^2 each. The building has a central core area housing two passenger elevators, two stairwells, washrooms, service shafts and a small sitting area. Except for the second and third floors, the floor space is fairly open, with very few individual offices.

The building has nine air-conditioning systems (Figure 1). Systems 1 and 2 are all-air two-deck systems that serve the fourth to the seventh floors; System 3 is a 100% outdoor air supply only system serving the centre core area. The outdoor air intake and exhaust air openings for the three systems are located in the north and south walls of the mechanical room directly above the seventh floor. Systems 3, 4 and 8 serve the third floor, and these three plus Systems 5, 6, 7 and 9 serve the ground, first and second floors. Two of the six systems for the lower four floors (Systems 6 and 9) are induction systems and serve the perimeter wall area; the other four (Systems 4, 5, 7 and 8) are all air two-deck systems and serve the interior area between the centre core and the perimeter wall. Outdoor air for the six systems comes from four outdoor air intake shafts located outside the building, about 5 m above grade level, beside the north and south walls (Figure 1).

Method of Measuring Air Change Rates

Air change rates were measured using the tracer gas decay method. The tracer gas, SF_6, was injected into every floor through the supply air ducts of Systems 1, 2, 6 and 9. After about an hour (for mixing), samples were taken consecutively from each floor at the return ducts for another hour, using an automated sampling system. The samples were pumped continuously, one after another, to an electron capture gas chromatograph for analysis.

To check how well the tracer gas mixes with the indoor air in such a building, additional samples were collected manually at 10-min intervals from two locations on each floor using a 60-mL syringe. Each sample was taken as follows: Just prior to sampling time, the 60-mL syringe was purged twice and then used to draw in a 50-mL sample of air. The sample was injected into a 20-mL evacuated glass test tube with a rubber septum-type stopper, of the type used to collect blood samples in medical laboratories. This meant that the sample was stored under pressure, which was relied upon later to drive the sample into the electron capture gas chromatograph for analysis.

The minimum air change rate was measured five times in May on calm days with the outdoor air dampers of the HVAC systems set at the minimum position. The average value of the five tests was about 0.5 air changes per hour.

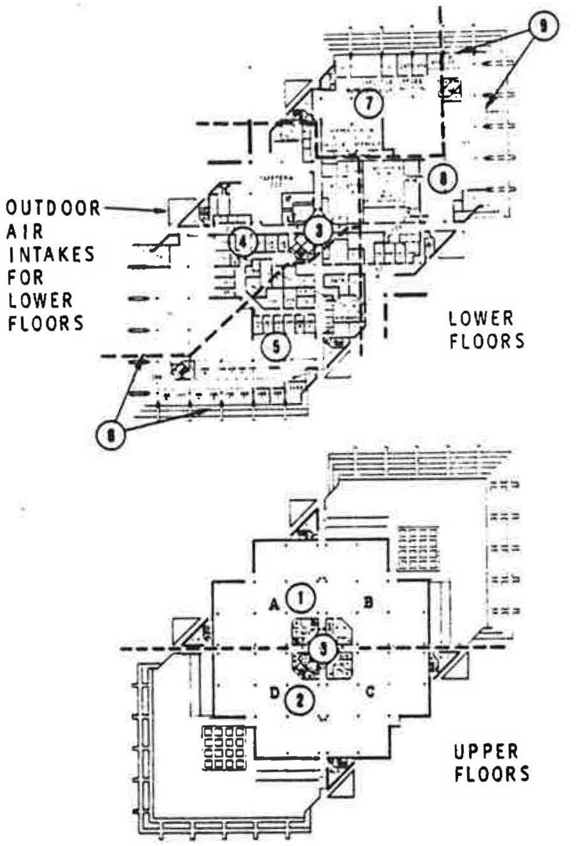

Figure 1. Typical floor plans showing the HVAC systems

Figure 2 shows the measured SF_6 concentrations as a function of time for various sampling locations. It indicates that the air change rates (as indicated by the slope of the concentration decay curve) from various sampling locations were similar. Concentrations in the occupied areas were also about the same, as were the concentrations in the return ducts. The tracer gas level was lower, however, in the floor space than in the return ducts for most floors.

To reduce the number of data, a sampling system (Figure 3) was used for subsequent measurements. As shown, the samples from the return ducts were drawn continuously through individual sampling tubes and mixed in a small reservoir. A valve was installed in each sampling tube to ensure that the gas flow rate from each sampling location was the same. The samples in the reservoir were used to determine the air change rate.

Assessment of Air Distribution

To check air distribution, a small amount of SF_6 was injected at a particular location to create a point source. Immediately following injection, tracer gas samples were taken at 10-min intervals at the main return ducts on each floor using an automated sampling system. These samples were pumped to the electron capture gas chromatograph for analysis. In addition, every 10 min eight samples each were collected manually from the first and second floors and four samples each from the third, fourth, fifth and sixth floors.

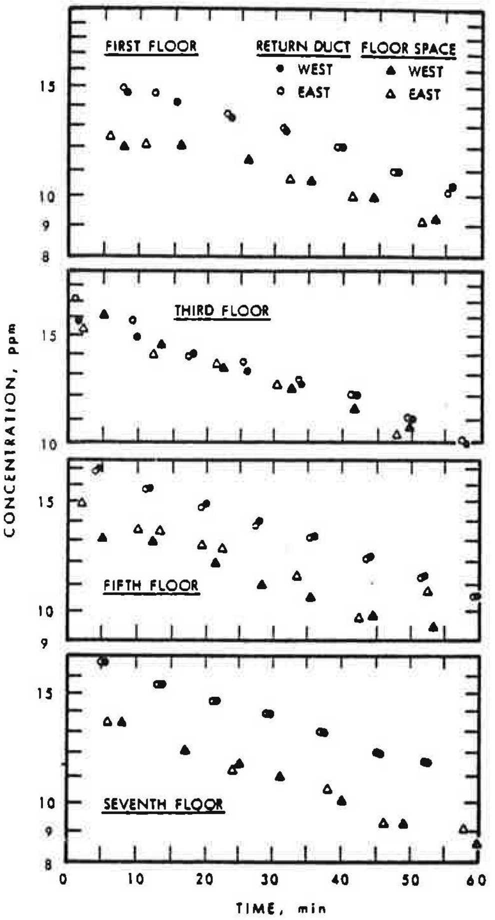

Figure 2. Air change rate measurements, SF_6 concentrations vs time for various sampling locations

The tracer gas concentrations of each sampling location are plotted against time in Figure 4. As shown, the tracer gas dispersed quickly in the zones served by the same HVAC system and then spread to other zones. Concentrations were nearly equal in less than 2 h. This suggests that if a contaminant source exists at the test location, the areas served by the same HVAC system will be contaminated quickly and that other areas will also be affected in less than 2 h. This suggests, again, that outdoor air will be distributed throughout the floor space in much less time because it enters every floor through both the exterior wall and the supply air registers. The test was repeated four times, each time with a new location as the contaminant source, and each time with similar results.

Measurements of CO_2 Concentrations

Figure 5 shows the automated system used for measuring CO_2 concentrations. It consists of 16 sampling pumps, a 16-port multi-position sampling valve, a main sampling pump, two detectors, a datalogger and a microcomputer.

CO_2 concentrations were measured at two locations on each of the seven upper floors: at the return duct and near the centre of the occupied area. On the ground floor measurements were taken at the return duct only. This provided one position on the 16-position sampling valve for sampling of outside air. Samples were drawn through individual PVC sampling tubes and analysed in real time on-site, using an infrared analyser (Figure 5). The maximum distance between a sampling location and the detector was about 150 m. To ensure that the sampling tube did not act as a sink or source (through absorption or desorption), a check was made by measuring a standard gas sample with and without the 150-m long sampling tube. No evidence of absorption was found as the difference between the two results was less than 1%.

Four CO_2 tests were conducted. The first three consisted of a one-week measurement period and the fourth was a one-day test. For the first two tests, the air change rate of the building was controlled manually by setting the outdoor air supply dampers of all HVAC systems at the 100% and 75% open positions, respectively. For the third test, the HVAC systems were operated on the automatic mode (i.e., the outdoor air supply dampers were adjusted automatically, based on the outdoor air temperature). The last one-day long test was conducted with all the outdoor air supply dampers set at the minimum open position. The actual air change rates were measured regularly during each test period and the results were averaged to obtain the mean

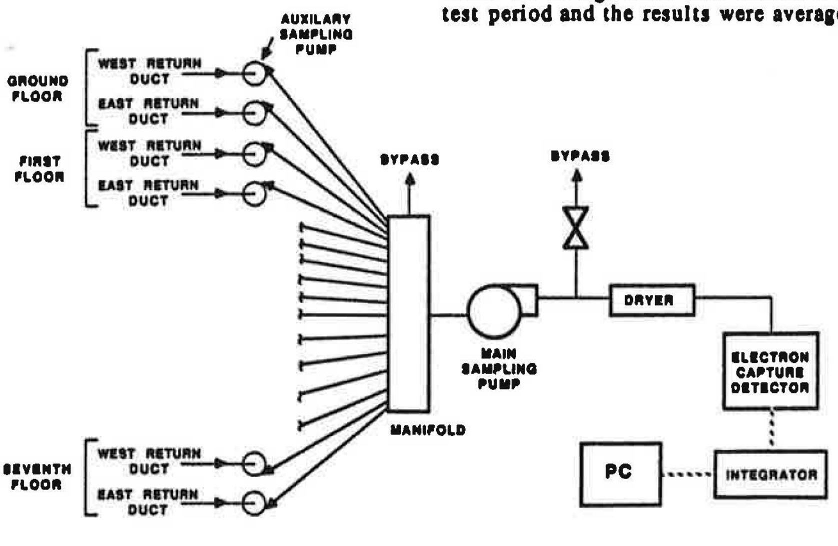

Figure 3. Automated tracer gas sampling system for measuring air change rates

air change rate (air change rates varied slightly from time to time because of weather changes).

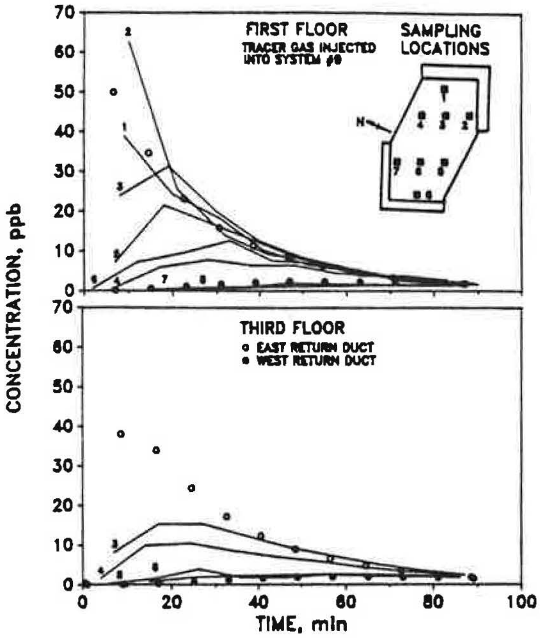

Figure 4. Air distribution patterns with tracer gas injected into supply air ducts of system No. 9

Figure 6 shows typical daily CO_2 concentration profiles measured on the third and sixth floors, where the maximum and the minimum overall indoor concentrations were observed. The measured air change rate was 0.61 ac/h. Results indicate that for the same floor level the CO_2 concentration measured in the occupied area (floor space) was generally lower than that measured in the return duct. The difference was more pronounced at the office floor (third) than at the library floor (sixth), but the reason for the discrepancy has not been determined.

The daily CO_2 concentration profiles in Figure 6 reflect the presence or absence of people. The indoor CO_2 level remained very near the outdoor level from midnight until about 7:30 a.m., when employees began to arrive for work. Indoor levels then increased, reaching the first peak concentration at 12 noon. The level subsequently decreased slightly during the lunch period and then increased again to reach an approximately steady-state concentration about 2 pm. From then on the CO_2 decreased steadily, reaching the outdoor level at about 12 midnight.

During each test, 15 CO_2 concentration profiles were measured each day. For weekdays, the daily maximum CO_2 level always occurred at the return duct on the third floor. For each of the three week-long tests, the five-workday average of the daily maximum CO_2 concentrations measured in the third floor return duct, C_{max}, was calculated. Values of C_{max} are plotted against corresponding average air change rates in Figure 7. The results show that C_{max} decreased as the air change rate increased, but the rate of decrease became much lower when the air change rate was greater than 1 ac/h.

<u>Relation Between CO_2 Concentration and Air Change Rate</u>

For buildings where occupants are the major source of CO_2, the relation between C_{max} and air change rate under steady-state conditions can be described by a simple mass balance equation.

[1] $$C_{max} = \left(\frac{G}{IV/N}\,\frac{3600}{1000}\right) 10^6 + C_o$$

where

C_{max} = maximum CO_2 concentration in the occupied space, ppm
C_o = CO_2 concentration in outdoor air, ppm
G = CO_2 generation rate per person, 0.005 L/s, for an activity level of 1.2 met units (office work)[1]
I = air change rate, ac/h

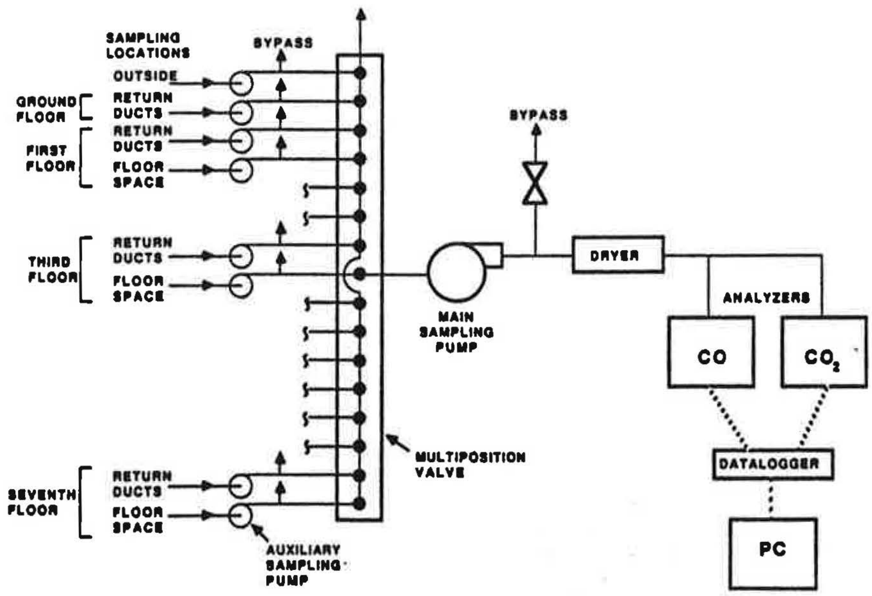

Figure 5. Automated sampling system for CO and CO_2 measurements

N = number of occupants
V = building volume, M^3

The constants 1000, 3600 and 10^6 are conversion constants to convert M^3 to L, h to s, and % to ppm, respectively.

To estimate the maximum CO_2 concentration for the test building the following assumptions were made: (1) because almost all the occupants were located on the first four office floors and there were no common return air ducts connecting these floors and the library floors, the volume of the first four office floors (67 000 m^3) was used; and (2) the number of occupants was assumed to be 400, which excluded all visitors. For comparison with measured values, the maximum CO_2 concentration predicted by Eq. 1 was also plotted in Figure 7. Except for one point, the agreement is within 5% of the predicted value.

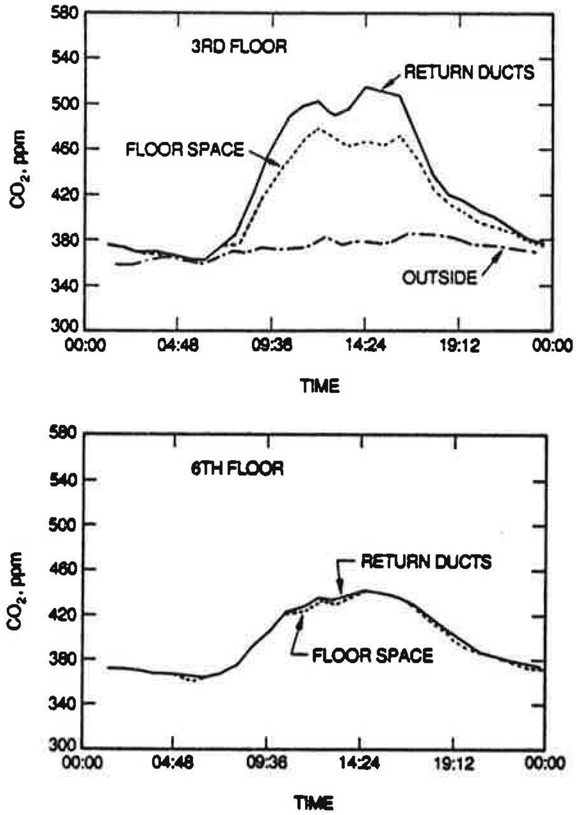

Figure 6. CO_2 profile for a typical weekday

DISCUSSION

The proposed plan has the following characteristics:

1. It includes a detailed assessment of the performance of HVAC systems.
2. It recognizes that extensive measurements of some contaminants are expensive and may not always lead to useful results. Thus, it reinforces the need for the project team to review periodically what has been done and, more importantly, to re-assess continually the original strategy in view of interim results.
3. It also includes a procedure for establishing the relation between concentrations and air change rates for selected contaminants. These relations are useful in determining outdoor air requirements.

For the test building, Figure 7 suggests a correlation between the daily maximum CO_2 concentration, C_{max}, and the air change rate during the work week. Further research is needed to verify that such a correlation exists for other buildings.

Because of this relationship and that between CO_2 concentration and intensity of body odour, it has been postulated that CO_2 may be used as an index of perceived air quality.[11] Several recent studies have reported that occupant complaints are common as the indoor CO_2 level reaches or exceeds 800 ppm.[12,13] For the test building, occupant complaints about poor air quality were reported when the CO_2 concentration in the office floors exceeded 450 ppm, which corresponded to a measured air change rate of about 1 ac/h, or 40 L/s per person on average. Where the air change rate was controlled to determine the relation between CO_2 concentration and air change rate, complaints increased with CO_2 level. When it exceeded 520 ppm, the number of complaints became unacceptable and the test was discontinued. Both studies[12,13] therefore suggest that the CO_2 level at which remedial action will be needed to reduce occupant complaints may vary from building to building. While it may be feasible to develop an air quality index based on CO_2 levels for a specific building, a general index suitable for all buildings may not be possible.

SUMMARY

A plan has been developed for assessing the air quality of non-industrial buildings. It was applied successfully to assess the indoor air quality of an eight-storey office/library building. A correlation between air change rate and CO_2 concentration was developed for the test building.

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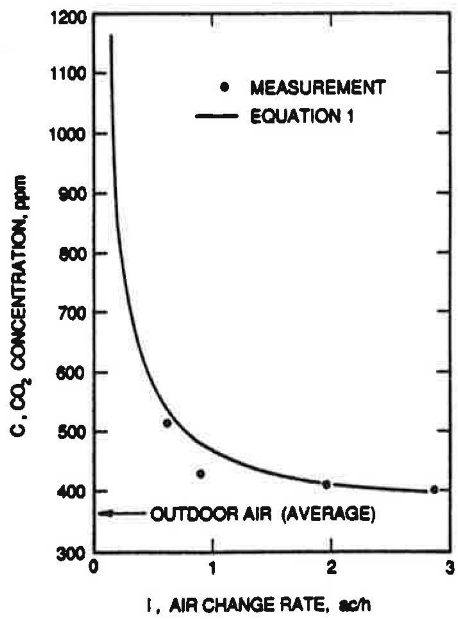

Figure 7. Daily maximum CO_2 concentrations vs air change rate for weekdays

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