Human Factors in Organizational Design and Management - II
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A PHASED TECHNIQUE FOR DIAGNOSING AIR QUALITY AND RELATED VENTILATION PROBLEMS

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We report on a phased system of integrated measurements of air quality, ventilation and occupant complaints that is relatively inexpensive yet leads to effective diagnosis of a building's IAQ and related ventilation problems. A case study is presented to illustrate the technique through case studies.

INTRODUCTION

Often a buildup of airborne contaminants due to the malfunctioning of the building mechanical ventilation system is suspected to be the cause of occupant comfort and health problems. The detailed monitoring of ventilation and air quality required to document possible system malfunctioning can be a time consuming and expensive undertaking, often with limited practical results. On the other hand, a phased program of gathering information from occupants combined with determining concentrations over time in various locations of easily measured key substances (CO and CO_2) plus inspection of other easily observed ventilation parameters can lead to more or less detailed judgments about the adequacy of the performance of a building's ventilation system. (1)

Phase 1 of the screening process includes:

a) General overview of the performance of the existing mechanical systems including site inspections and review of plans.

b) Administration of a Work Environment Survey Questionnaire to all building occupants as a means of documenting environmental problems and symptoms reported in the building and to locate clusters of complaint areas for detailed monitoring.

Phase 2 of the screening process includes:

a) Measurement of carbon dioxide as an indicator of a build-up of contaminants generated indoors from occupants and equipment.

b) Measurement of carbon monoxide as an indicator of combustion byproducts infiltrating from the outside, especially from parking garages or from other sources of indoor combustion.

Phase 3 of the screening process includes:

a) Measurement of air exchange rates with tracer gas to determine the total ventilation rate within the building as well as the pattern of air movement through the building including air leakage from potential indoor pollutant sources such as parking garages.

One complete building evaluation is used here to illustrate the methods used.

The Building

In addition to the building under study, a control building was also included in the investigation for comparison purposes. Each building is occupied by approximately 130 office employees.

The study building is a 4 story, 10 year old, sealed, mechanically ventilated and air conditioned office building. This building is similar to much of the low-rise office space existing throughout North America.

The control building is also a 4 story office building. However, it is approximately 50 years old and is equipped with operable windows for ventilation and radiators for heat.

PHASE 1: SITE INSPECTION AND QUESTIONNAIRE SURVEY

Description of Mechanical Systems

The study building has two mechanical ventilation systems, one services the core, the other the perimeter office space. The core area offices are ventilated by a constant volume ducted system providing approximately 2,000 litres per second (l/s) of outdoor air distributed equally between the four office floors. Outdoor air is delivered directly from the roof top mechanical penthouse to the centre of the ceiling plenum space on each floor. Ceiling mounted heat pumps then draw a mixture of outdoor and return air from the ceiling plenum space, temper it and diffuse the mixed air into the office area through grills in the suspended ceiling.

A second system provides a mixture of outdoor and return air to the perimeter office space through perimeter console or fan coil heat pump units. The perimeter console units are located below the windows on three sides of the building. All console units draw air directly from the outdoors, except six located along the east facing side of the first floor. These six units draw outdoor air from a duct that passes through the basement parking garage.

The Survey of Occupants' Perceptions

The survey questionnaire was administered to all of the office occupants of both buildings. A predominance of environmental complaints such as inadequate ventilation, dry and stuffy air were identified among building occupants of the study building compared to the control building. Symptoms reported most prevalently among occupants of the study building were of mucous membrane irritation such as the eyes, nose and throat. Symptoms also included headaches and fatigue. Of the four floors of the study building the third floor was found to have the highest incidence of both environmental complaints and symptoms.

PHASE 2: ENVIRONMENTAL MEASUREMENTS

Carbon monoxide and carbon dioxide were measured in both buildings two times a day on work days during a continuous three week period. Measurements were taken at selected sites in the occupied office space on each floor in the study building and on two floors of the control building. Outdoor measurements were taken on the roof of the study building.

Carbon Monoxide

Table 1 shows concentrations measured inside the study building (including the basement parking garage) outdoors on the roof and in the control building. The mean concentrations of CO do not vary greatly by floor or by morning or afternoon. The highest CO concentrations were found in the basement parking garage, with morning and afternoon means of 11.4 ppm and 15.3 ppm. The CO concentration on all floors of the study building were similar and did not vary significantly by time of day. Concentrations were, however, slightly lower in the control building.

The CO concentrations encountered in both buildings are high in comparison with those measured in similar buildings. Figure 1, extracted from the Building Performance Database[4](2), shows the distribution of CO in similar buildings. (3)

Results of statistical tests of CO measurements taken in the parking garage, outdoors and at sites on each occupied office floor of the study building, showed that concentrations of CO in the office space of the study building are affected by both outdoor sources and fumes from the parking garage in the basement. The outdoor contribution to indoor CO is consistent throughout the building. CO from the parking garage, although permeating the whole building, is strongest on the first floor and progressively weakens by floor level. Insofar as CO is an indicator of vehicle exhaust fumes, the conclusion is compelling that part of the indoor problem is created by the many irritants in exhaust gases and aerosols.

Carbon Dioxide

Carbon dioxide measurements taken in the study building, outdoors on the roof and in the control buildings are shown in Table 2. Two trends are apparent in the study building:

1. CO_2 tends to be higher on the upper two floors.
2. CO_2 concentrations increase in the afternoon.

The patterns of daily variation and variation between floors for CO_2 are shown in graphs of Figure 2. There are sharp contrasts between morning and afternoon as well as differences in CO_2 between floors. Morning concentrations of CO_2 show a strong positive relationship between indoor and outdoor levels. However, this relationship is not evident for afternoon CO_2 concentrations.

In the mornings, indoor CO_2 concentrations are strongly influenced by the outdoor levels. However, this changes over the day, with outdoor CO_2 no longer a main determinant of indoor CO_2 in the afternoon. Results show that outdoor CO_2 has a strong effect on the increase of indoor concentrations in the morning. However, that effect is no longer present in the afternoon after the building has been occupied. It is therefore likely that the ventilation system is unable to keep pace with occupant generated CO_2 and, by extension, that the ventilation system is unable to keep pace with accumulation of other contaminants generated by sources in the building.

PHASE 3: VENTILATION SYSTEM PERFORMANCE

Phase 3 consisted of a number of tests and evaluations performed to:

1. Measure the amount of air being provided to the building occupants by tracer gas and smoke pencil evaluations.

2. Determine the path by which polluted air from the basement parking garage enters the occupied office floors, by tracer gas and smoke pencil evaluations.

Measurement of Evaluation of Outdoor Air Supply

Tracer gas was used to measure the amount of outdoor air supplied to the entire building, the amount of outdoor air provided to occupants of each floor and to the first floor conference room. In addition, the percentage of outdoor air provided by two of the perimeter console units was determined.

Movement of air currents in the building were visually determined by following the movement of "smoke" produced by smoke pencils.

Table 3 shows the total air supply on each floor provided by both perimeter and core mechanical ventilation systems. Ventilation rates for each floor comply with the current ASHRAE standard of 10 l/s/person.

Table 4 presents results of testing the amount of outdoor provided by two of the 88 console units that comprise the perimeter mechanical system. The total air delivered by each console unit is approximately 100 l/s on maximum setting and the fresh air component is 18-20 l/s. By extrapolation, if all 88 console units were operating at maximum capacity, then they would supply approximately 1,760 l/s/person of outdoor air to the building.

Table 5 shows that while the supply of outdoor air to the first floor as a whole is adequate, the supply of outdoor air to the conference room on the first floor (presuming a population of 20 people) is inadequate. While the ASHRAE standard suggests a supply of 17.5 l/s/person of outdoor air for conference rooms, the existing system supplies only 3.5 l/s/person. From an analysis of the building plans, it was also determined that due to problems with ventilation design and efficiency other densely populated areas of the building may also be poorly supplied with fresh air.

Qualitative tests of air circulating and mixing patterns made using smoke pencils showed good mixing of air in the occupied office space.

Determination of Pollutant Pathways from Garage

Carbon monoxide measurements collected as part of Phase 2 of the three-part screening process showed a strong correlation between the concentrations of CO in the garage and in the first floor adjacent to six perimeter console units. A sheet metal duct providing outdoor air to the six perimeter console units located along the east side of the first floor was suspected to be the pathway for the passage of CO and other pollutants from the garage into the building. This duct passes through the garage and was found by smoke pencil tests to entrain air from the garage when the consoles were operating. A tracer gas test was conducted to verify the penetration of air from the parking garage into the first floor office space through this duct.

Table 6 shows the results of releasing tracer gas into the garage and then measuring the concentrations of tracer gas penetrating the first and second floors. Tracer gas was detected throughout the first floor, with higher concentrations on the east side near the six consoles supplied with outdoor air by the duct passing through the garage. No tracer gas, however, had penetrated into the second floor. These results show that the duct passing through the parking garage is the main pathway of penetration of contaminated air from the garage into the first floor.

DISCUSSION

The phased screening approach to field monitoring of indoor air quality and ventilation system performance now tested on a wide variety of buildings in the U.S., Canada and England, provides the components for development of a standard method for undertaking building evaluations. Adoption of this standard methodology for evaluating indoor air quality and ventilation system performance, will benefit the investigator as well as the building owner/tenant by allowing the comparing of measurement collected in any building to data from other buildings. As more studies are undertaken, a baseline of data will also be available for comparison purposes. In addition, use of standardized approach will provide the investigator with a check against overlooking pertinent information that may lead to practical and effective solutions.

REFERENCES

(1) Sterling, E.M., McIntyre, E.D., Collett, C.W., Meredith, J., Sterling, T.D., Sick buildings: Case studies of tight building syndrome and indoor air quality investigations in modern office buildings, Environmental Health Review. (1985) Vol 29(3):11-19.

(2) Theodor D. Sterling Limited (TDS), The Building Performance Database User's Guide, (1984). (Available on request from TDS Limited.)

(3) Sterling, E.M., Sterling, T.D., Pollution concentration in buildings, Proceedings. AIA Research and Design '85, Los Angeles, CA., March 14-18, 1985. 279-184.

FOOTNOTES

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4 Information about use of and access to the Building Performance Database can be obtained by contacting Theodor D. Sterling Ltd., #70-1507 W. 12th Avenue, Vancouver, B.C. Canada V6J 2E2, (604) 733-2701.

TABLE 1

MEAN CARBON MONOXIDE CONCENTRATIONS AND (NUMBERS OF OBSERVATIONS) IN PARTS PER MILLION, BY FLOOR FOR STUDY BUILDING, INCLUDING BASEMENT, CONTROL BUILDING AND OUTDOORS

	Study Building						Control Building	
	Basement Parking Garage	Floor 1	Floor 2	Floor 3	Floor 4	Roof	Floor 3	Floor 4
AM	11.4 (14)	8.9 (30)	7.8 (15)	8.2 (15)	7.8 (15)	8.7 (15)	6.8 (15)	7.5 (15)
PM	15.3 (13)	7.9 (30)	7.5 (15)	7.8 (15)	7.4 (15)	5.9 (15)	7.3 (15)	7.6 (15)

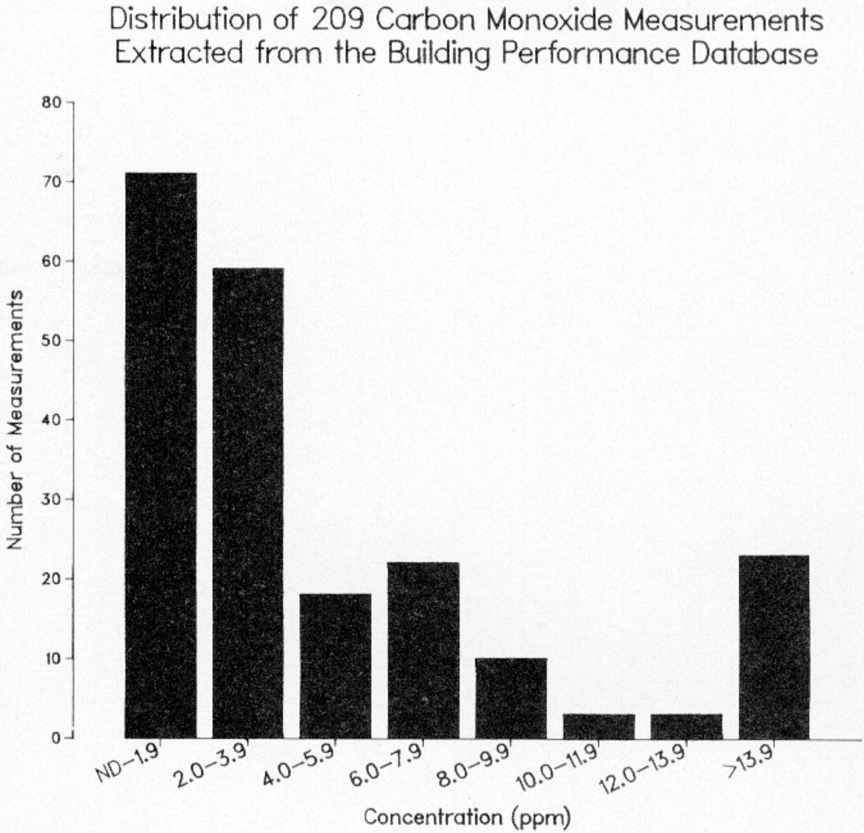

Distribution of 209 Carbon Monoxide Measurements
Extracted from the Building Performance Database
Number of Measurements
0
10
20
30
40
50
60
70
80
ND–1.9
2.0–3.9
4.0–5.9
6.0–7.9
8.0–9.9
10.0–11.9
12.0–13.9
>13.9
Concentration (ppm)

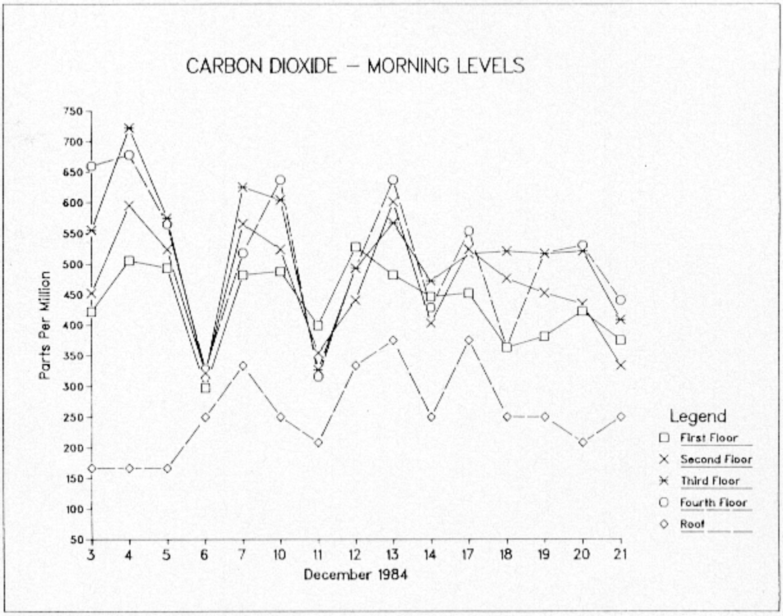
FIGURE 1

TABLE 2

MEAN CARBON DIOXIDE CONCENTRATIONS AND (NUMBERS OF OBSERVATIONS) IN PARTS PER MILLION BY FLOOR FOR STUDY BUILDING, CONTROL BUILDING AND OUTDOORS

	Study Building					Control Building	
	Floor 1	Floor 2	Floor 3	Floor 4	Roof	Floor 3	Floor 4
AM	434.9 (106)	468.4 (103)	516.2 (84)	509.6 (104)	255.6 (15)	533.3 (15)	483.3 (15)
PM	471.2 (104)	491.6 (105)	545.5 (86)	509.6 (15)	288.9 (15)	408.9 (15)	433.3 (15)

FIGURE 2 Mean Morning and Afternoon Carbon Dioxide Concentrations Measured in the Study Building



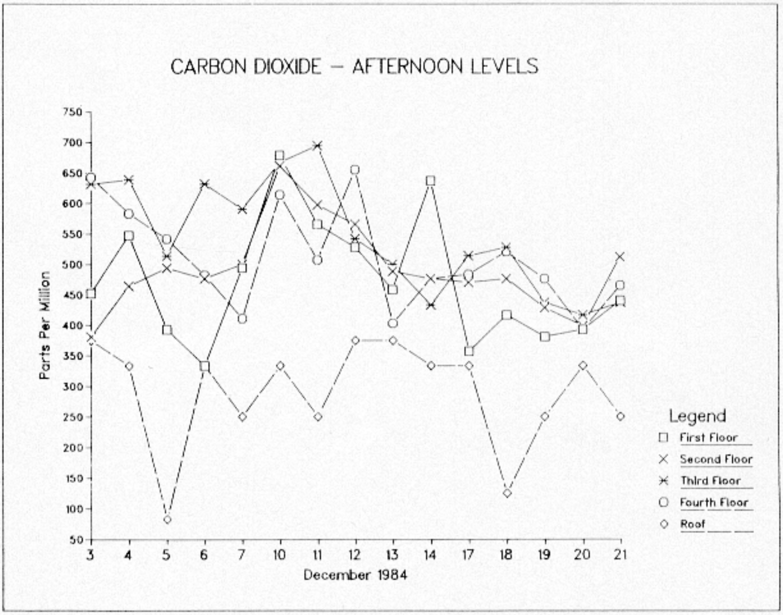


TABLE 3

TRACER GAS TESTS OF OUTDOOR AIR SUPPLIED TO EACH FLOOR OF THE STUDY BUILDING*

	Total Outdoor Air Flow	Actual Population	Outdoor Air Supply Per Person
First Floor	630	45	14
Second Floor	737	33	22
Third Floor	800	43	18
Fourth Floor	676	28	24

*In litres per second, 1/s.

TABLE 4

TRACER GAS TESTS OF OUTDOOR AIR SUPPLY FROM TWO CONSOLE UNITS

	Unit #1	Unit #2
% Outdoor Air Supplied By Console Units	18%	22%

TABLE 5

OUTDOOR AIR SUPPLY

	Total Outdoor Air Flow	Outdoor Air Supply/Person	Air Change/Hour
Conference Room	69	3.5**	1.5
First Floor	630	14.	0.6

*In litres per second, l/s.

**Based on 20 persons (ASHRAE Standard for a conference room is 17.5 l/s/p)

TABLE 6

TRACER GAS TESTING OF LEAKAGE PATTERNS FROM THE PARKING GARAGE

	Nitrous Oxide Levels	
	First Readings*	Second Readings*
Parking Garage	3.52	2.40
First Floor East	0.68	0.65
First Floor West	0.32	--
Second Floor	--	ND**

*Readings are in absorption units and are only relative

**Non-detectable

--No data collected