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INDOOR AIR QUALITY ASSESSMENT IN AN OFFICE-LIBRARY BUILDING: PART II—TEST RESULTS

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ABSTRACT

A detailed investigation of the indoor air quality of a fully air-conditioned eight-story office/library building was carried out. The main purpose of the investigation was to determine the cause(s) of occupants' complaints, which included stuffy air, headaches, eye irritation, prolonged allergic reaction, and a decline in health.

Details of the study are presented in two papers. The test plan and the analytical procedures employed are discussed in Part I (Shaw et al. 1991). This paper, Part II, presents the results and recommendations for remedial measures in the building.

INTRODUCTION

Complaints of unsatisfactory air quality by occupants of an air-conditioned eight-story office/library building have been received repeatedly since 1981. These included a formal claim of prolonged allergic reaction and a decline in health submitted by an employee working in the southern and southeastern areas of the first floor. Also, employees working in the photocopy areas on the fifth and sixth floors complained of headaches, eye irritation, and stuffy air.

Two pilot studies were conducted to determine the cause(s) of the complaints; neither was sufficiently extensive to identify all possible causes (Shaw et al. 1991). Continued complaints prompted this investigation, which was undertaken between March 1987 and August 1988.

This paper presents the results of the third investigation and gives recommendations for remedial measures in the building. A companion paper discusses the assessment plan and the measurement methods employed (Shaw et al. 1991).

TEST BUILDING

The building is a fully air-conditioned eight-story library/office building in which the first four floors contain offices and the remaining four house library stacks. The floor areas of the lower three floors and upper five floors are about 4,800 m² and 2,400 m² each, respectively. The building has a central core area housing two passenger elevators, two stairwells, washrooms, service shafts, study carrels, and small sitting areas. Except for the second and third floors, the floor space is fairly open, with very few individual offices. Since 1984, smoking has been restricted to a single room on the ground floor. A large amount of photocopying is performed daily in support of the building's role as a library. Most is performed on the sixth floor, where up to six photocopiers may be used continuously between 9 a.m. and noon and from 2 p.m. to 4 p.m.

This building has nine air-conditioning systems (Figure 1). Systems 1 and 2 are all-air, two-deck systems that serve the fourth through seventh floors; system 3 is a 100% outdoor air, supply-only system serving the central 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

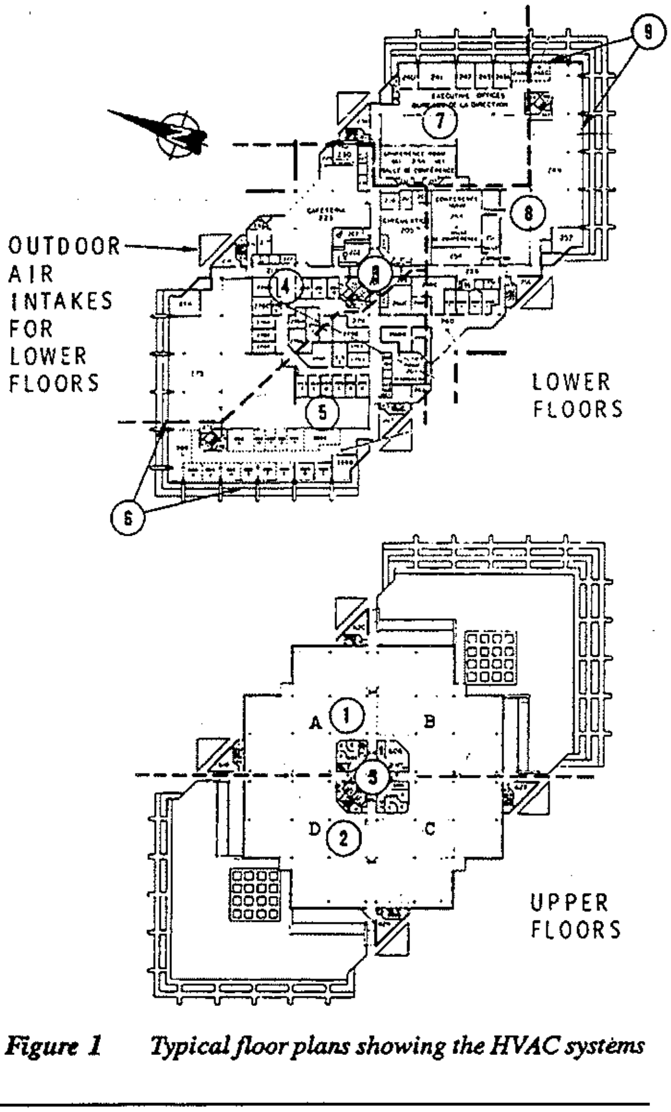

Figure 1 Typical floor plans showing the HVAC systems

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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 central core and the perimeter wall. Outdoor air for the six lower systems comes from four intake shafts located outside the building, about 5 m above grade level, beside the north and south walls (see Figure 1).

RESULTS AND DISCUSSION

The results are discussed in terms of the performance of HVAC systems and the levels of chemical, physical (particulates), and biological contaminants.

In the evaluation of the observed contaminant levels, two documents were used extensively: *ASHRAE Standard 62-1981R, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 1986) and Health and Welfare Canada (HWC) Guideline, *Exposure Guidelines for Residential Indoor Air Quality* (HWC 1987). The HWC guideline is intended for residential buildings, where there can be 24-hour-per-day exposure and, therefore, the requirements may be more stringent than those for an office environment.

It is recognized that, in general, multiple contaminants exist in the indoor environment, and some interaction in their health effects may occur. While the relevant guidelines/standards have made some attempts to consider such effects, due to inadequate data, the recommended limits deal only with individual contaminants in most cases (HWC 1987).

Performance of HVAC Systems

HVAC system performance is evaluated by its ability to supply an adequate amount of "clean" outdoor air for ventilation, to distribute the outdoor air uniformly within the building, and to maintain a thermally comfortable environment.

Adequacy of Ventilation Air: Air Change Rates Ventilation air comes from two sources: outdoor air supplied directly by HVAC systems and air infiltration through cracks and unintentional openings in the building envelope. As air infiltration is weather dependent, the minimum ventilation rate occurs when the weather is warm and calm and the outdoor air dampers are set at their minimum position.

The minimum ventilation rate of the building was measured five times using the tracer gas decay technique on calm days with the outdoor air temperatures near 20°C. The measured ventilation rates at different locations varied between 0.4 and 0.6 air changes per hour (ach) due to imperfect mixing, which is common for buildings with complex layout. The results indicated that even the lower value, 0.4 ach (equivalent to about 18.6 L/s per occupant), exceeds the ASHRAE ventilation requirement of 10 L/s per person for an office building.

Air Distribution Four tracer gas tests of air distribution in the building were conducted. Figure 2 shows the result of the first test, during which a small amount of SF_6 was injected into the main supply duct of HVAC system 9 to create a local source. As shown, the tracer dispersed quickly within the zone served by HVAC system 9 and then spread to other zones. Concentrations at all sampling locations were nearly equal within 80 minutes. This suggests that a contaminant in the building will spread rapidly from its source to areas served by the same HVAC system and that other areas will also be affected within 80 minutes. Four injection locations were tested, each yielding similar results.

In the absence of a formal guideline or standard and experimental data from similar buildings, a less rigorous criterion was used to assess the air distribution of this building. As indicated in Figure 2, tracer gas levels throughout the particular HVAC system zone were nearly equal within 30 minutes, which is less than the 60 minutes typically allowed for achieving adequate mixing when conducting air change rate measurements in buildings with the tracer gas decay method. This suggests that the air distribution system of this building performed as well as those in other buildings where tracer gas decay tests have been conducted.

Reentrainment of Exhaust Air To determine whether exhaust air reentered the building, a small amount of tracer gas was injected into an exhaust system and the concentrations at the outdoor air intake of each HVAC system were measured. All exhaust systems of the building were checked. Minimal reentry of exhaust air was observed.

Installation and Operational Problems with HVAC Systems Visual inspections revealed that too many bends exist in the outdoor air supply ducts of some of the HVAC systems. This is particularly true for the systems serving the office floors. The problem was first noticed during the measurement of microbial contaminants in system 8 (serving one complaint area). The numbers of colony-forming units in the return air and in the air immediately downstream of the outdoor air damper were almost identical, suggesting that no fresh air was entering the system. A follow-up inspection of this supply air duct revealed that almost no fresh air was supplied when the outdoor air damper was partially closed (e.g., at 75% open position). The problem was believed to result from a combination of high fluid resistance in the supply air duct, an oversized return air damper, and a powerful return air fan. Investigation of the other systems revealed that this condition was most severe in system 8.

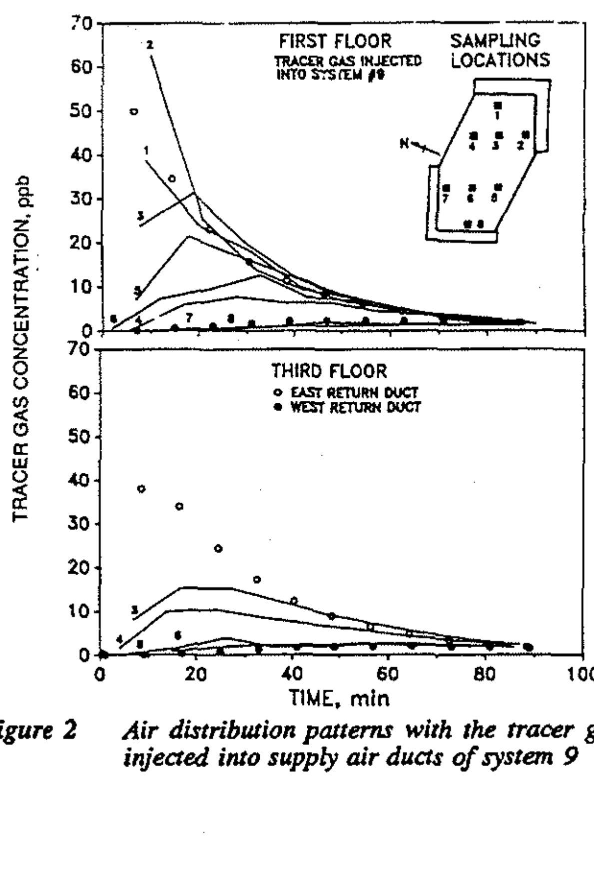

Figure 2 Air distribution patterns with the tracer gas injected into supply air ducts of system 9

Visual inspection revealed very low airflow rates from several system 4 supply air registers. The problem was corrected upon opening an inadvertently closed fire damper.

Thermal Comfort In the winter of 1988, thermal comfort conditions at six locations, including offices with large windows, internal offices, and the complaint areas, were assessed according to *ASHRAE Standard 55-81* (ASHRAE 1981). Spot readings of relative humidity, air velocity, and dry-bulb and radiant temperatures were recorded at three elevations above floor level (7, 75, and 185 cm) for each location. Conditions at two locations were found to be outside the comfort envelope specified by ASHRAE for persons performing light, mainly sedentary activities under winter conditions. In particular, a second-floor office in the southern perimeter zone was too warm (26.1°C at 185 cm) and drafty (air velocities exceeded the recommended upper limit of 35 cm/s). Based on these initial observations, further detailed study was conducted in the first-floor complaint area (Room 157) and at six locations on the second floor. At each site, the parameters described above were recorded at 75 cm above floor level for a six-hour period.

Figure 3 shows the results for Room 157, the complaint area on the first floor. Temperatures and air velocities were within acceptable ranges. Relative humidities, however, ranging from 17% to 21%, were well below HWC guidelines. The observations recorded at 9:30 a.m., 10:00 a.m., noon, and 2:00 p.m. are plotted on the ASHRAE comfort chart for winter conditions in Figure 4. All four results fell outside the comfort zone.

Similar plots are given in Figure 5 for the second-floor sampling locations. As shown, the temperatures in Rooms 249 (a south perimeter office), 263B (an internal office), and 269D (a west perimeter office) were higher than would normally be considered comfortable under winter conditions. Since all these rooms have large windows and/or skylights, the observations suggest that the existing HVAC systems were not capable of handling the resultant large solar loads.

Chemical Contaminants and Particulate Matter

Concentrations of the following contaminants within the building were monitored: carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), total volatile organic compounds (TVOC), formaldehyde (HCHO), and particulate matter (suspended and settled). Some of these (e.g., CO, CO_2, and HCHO) were selected because they are listed in various standards as typical indoor air pollutants. Others (e.g., TVOC) were chosen based on the results of the two previous studies.

The HWC guidelines specify acceptable long- and short-term exposure ranges ("ALTER" and "ASTER," respectively). ALTER is defined as the concentration range to which it is believed from existing information that a person may be exposed over a lifetime without undue risk to health. ASTER is that concentration range to which it is believed from existing information that a person may be exposed over a specified time period without undue risk to health.

Carbon Monoxide (CO) CO concentrations were monitored for a three-month period at the return duct and near the center of the occupied area on each of the seven upper floors. Measurements were also conducted on the ground floor at the return duct and at one location outside the building near the roof level. Sampling locations are summarized in Figure 6. On weekdays, the measured

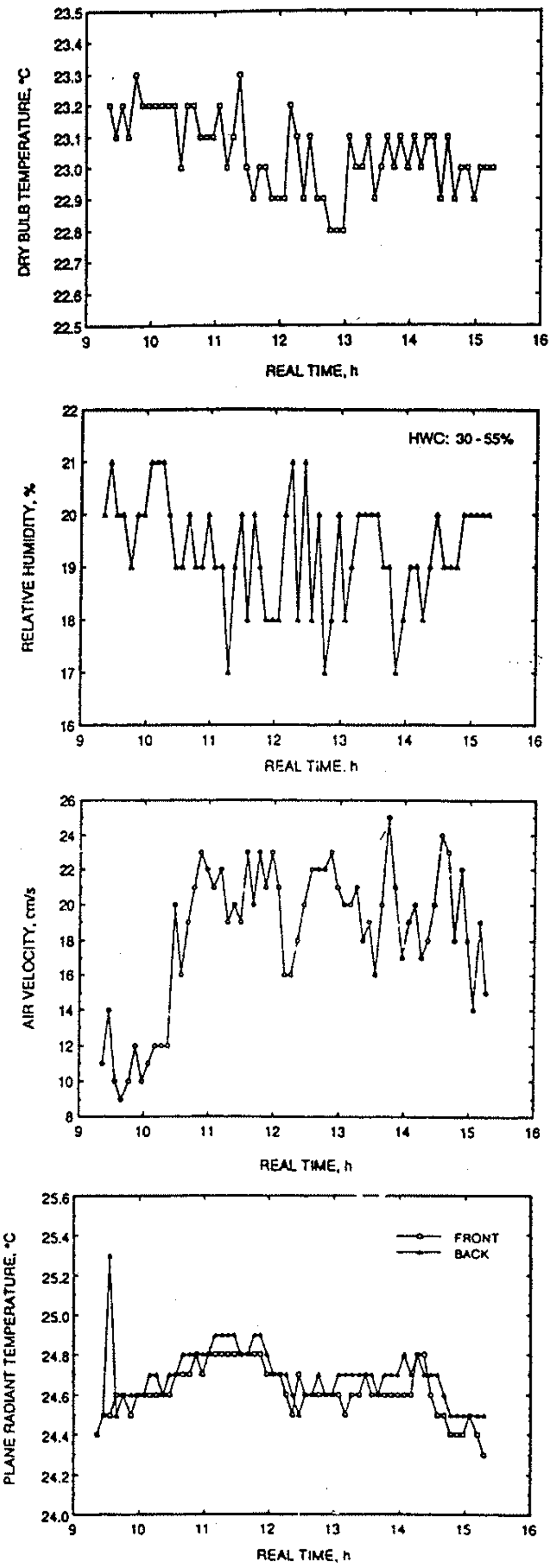

Figure 3 *Air temperature, relative humidity, air velocity, and radiant temperature profiles for room 157*

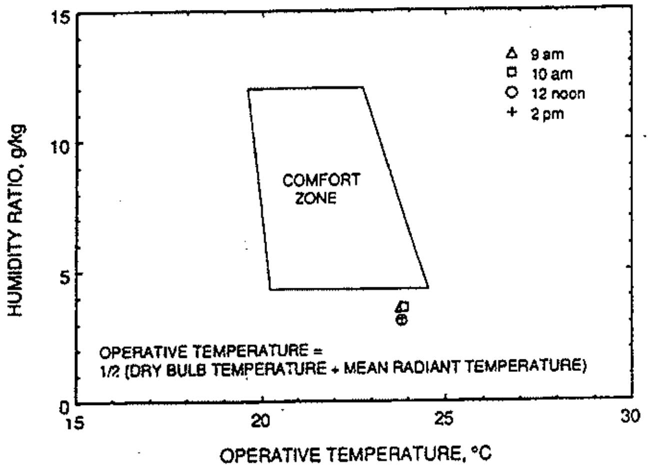

Figure 4 *Degree of thermal comfort vs. time for room 157*

concentrations inside the building varied from 1 ppm to 7 ppm, while outside concentrations ranged from 1 ppm to 3 ppm. The CO concentrations in this building were, therefore, within the HWC ALTER limit of 11 ppm (average concentration) for an eight-hour exposure.

Carbon Dioxide (CO_2) CO_2 measurements were conducted for a one-week period with the HVAC systems operating in the automatic mode (i.e., the outdoor air supply dampers were automatically adjusted based on the outdoor air temperature). Sampling locations were the same as those described for CO monitoring (Figure 6). The measured concentrations during office hours varied from 340 ppm to 440 ppm, and the air change rates ranged from 0.8 ach to 1.0 ach. The maximum concentrations reported in the two previous studies were 370 ppm and 480 ppm. This building thus meets the recommendations of both ASHRAE (1,000 ppm) and HWC (ALTER limit: 3,500 ppm).

Relation Between CO_2 Concentration and Air Change Rate In the absence of significant combustion sources, the concentration of CO_2 in indoor air depends on the occupancy load and is inversely related to the outdoor air supply rate. As well, indoor levels of contaminants such as odors can be controlled by increasing ventilation Thus, while CO_2 is not a cause for occupant complaints, it may be used as an indicator of ventilation rate adequacy for controlling levels of certain contaminants that may be correlated with CO_2 concentrations (Shaw 1988b).

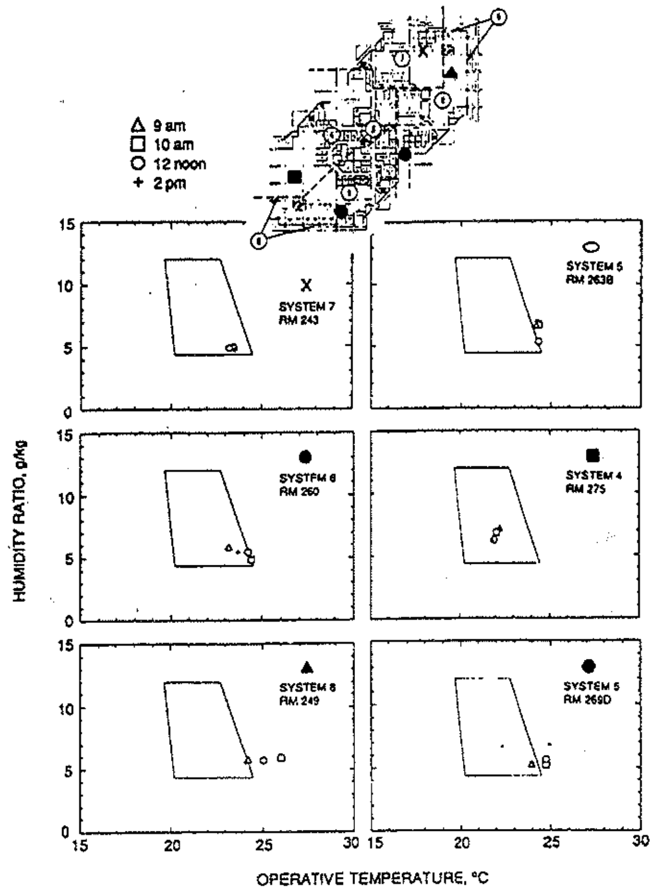

Figure 5 *Degree of thermal comfort vs. time for various zones*

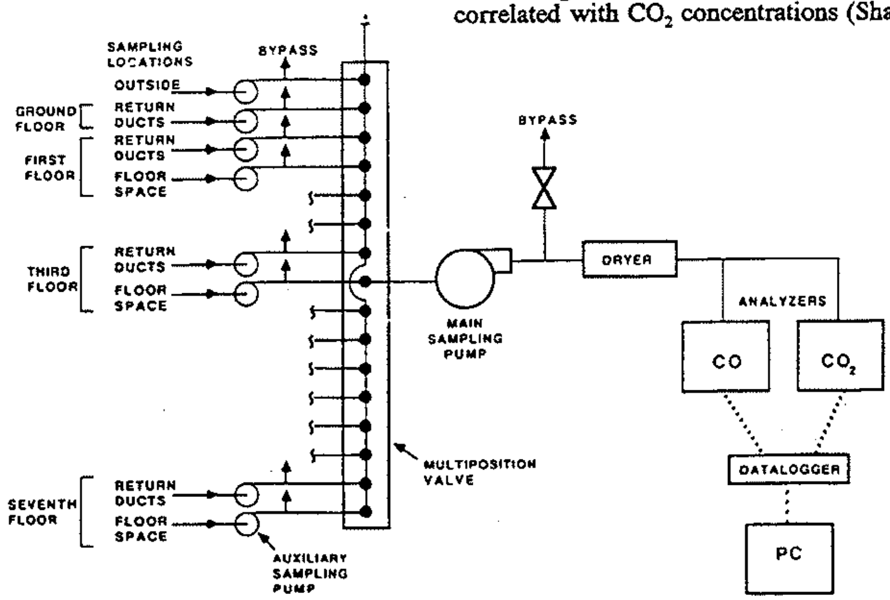

Figure 6 Automated sampling system for CO and CO_2 measurements

To obtain the relationship between CO_2 concentration and air change rate for this building, three additional tests were conducted. Concentrations of CO_2 were measured at the same locations as in the previous test; thus, 15 CO_2 concentration profiles were measured each test day. 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. Each of these tests lasted one week. The third test was conducted on a single day with all the outdoor air supply dampers set at the minimum open position. To account for changing weather conditions, the air change rates were measured regularly during each test period, and the results were averaged to obtain the mean air change rate.

Figure 7 shows typical daily CO_2 concentration profiles measured at two locations 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 ach. At about 7:30 a.m., indoor levels increased, reaching the first peak concentration at noon. The level subsequently decreased slightly during the lunch period and then increased again to reach an approximately steady-state concentration at about 2 p.m. The CO_2 concentration decreased steadily after 4 p.m., reaching the outdoor level at about midnight. For weekdays, the daily maximum CO_2 level always occurred at the third-floor return duct.

The daily maximum CO_2 concentration measured in the third-floor return duct was determined for each test day. For each of the week-long tests (three, counting the previous automatic mode test), the five values from working days were averaged to give a mean daily maximum CO_2 concentration, C_{max}. These values of C_{max}, plus the single data point for the minimum outside air test, are plotted against corresponding average air change rates in Figure 8. The results show that C_{max} decreased as the air change rate increased. The rate of decrease became much lower when the air change rate was greater than 1 ach.

The relation between C_{max} and the air change rate for this building under steady-state conditions was also obtained from the equation (Shaw 1988b):

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

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 1.2 met unit activity level (office work)
I = air change rate, ach
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. For comparison with measured values, the calculated maximum CO_2 levels are also shown in Figure 8. Except for one point, the agreement is within 5% of the calculated value.

When the air change rate was controlled to determine its influence on CO_2 concentration, occupant complaints increased with CO_2 level. At levels above 520 ppm, the number of complaints forced the discontinuation of the test. This suggests that, for this building, there is a correlation

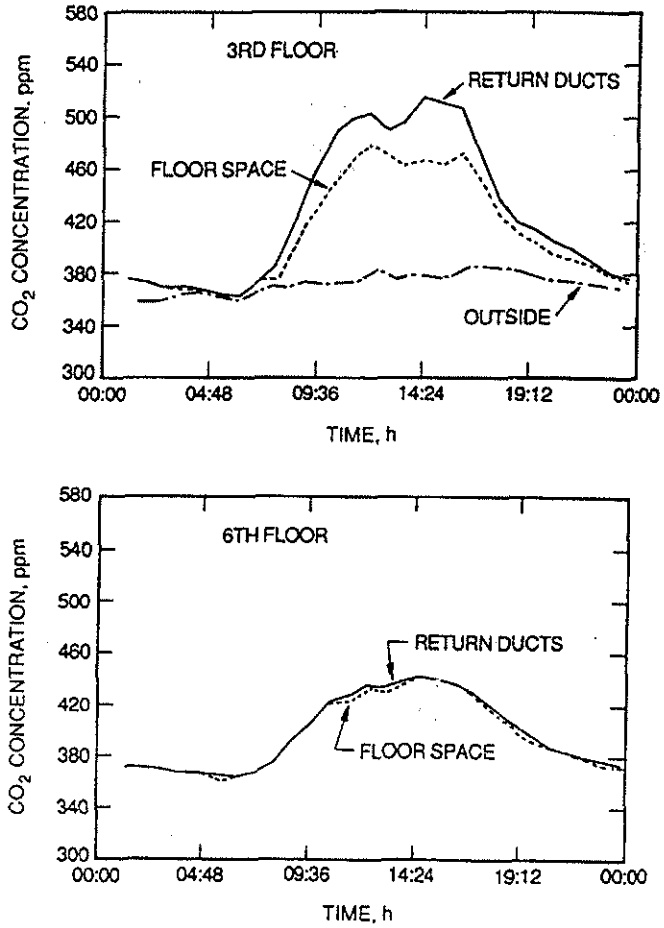

Figure 7 CO_2 *profile for a typical weekday*

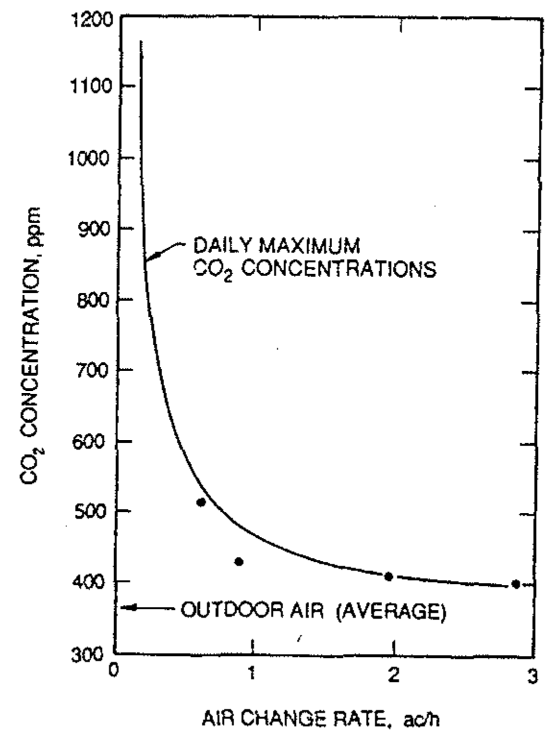

Figure 8 *Daily maximum* CO_2 *concentration vs. air change rate for weekdays*

between CO_2 level (used as an index for indoor air quality) and occupants' complaints. Further research is needed to verify that such a correlation also exists for other buildings.

Nitrogen Dioxide (NO_2) Nitrogen dioxide (NO_2) is the only oxide of nitrogen considered to be detrimental to human health at concentrations that may be encountered in indoor air (HWC 1987). The primary outdoor sources of NO_2 are vehicular and industrial emissions. As the outdoor air intake for system 8 is adjacent to the building's south-eastern shipping and receiving dock, it was felt that vehicular exhaust could enter the building by this route. NO_2 was continuously monitored, first at Room 157 (served by system 8) and then in the outdoor air intake of system 8, for a month at each location. The measured concentrations were less than 0.04 ppm, which is within both the HWC short-term acceptable limit of 0.25 ppm (one-hour average concentration) and the long-term acceptable limit of 0.05 ppm.

Total Volatile Organic Compounds (Total Hydrocarbons) TVOC concentrations in the building were measured indirectly by continuously monitoring the concentrations of total hydrocarbons (THC) at three locations: the photocopying area on the sixth floor, where previous studies revealed maximum concentrations, and the return ducts of systems 2 and 8, which represent the average concentration of the library stacks area and the office floors, respectively. The measured concentrations during office hours ranged from 3 to 68 mg/m^3 for the sixth floor, 3 to 11 mg/m^3 for the library stacks area, and 1 to 2 mg/m^3 for the office floors. The air change rates during the measurement period ranged from 0.8 to 1.0 ach.

Figure 9 shows typical daily TVOC concentration profiles measured at the three locations. The results for the sixth floor reflect daily periods of peak photocopying activity at about 9 a.m. and 2 p.m. Levels on this floor rapidly returned to background values after normal office hours. The VOC profile in the system 2 return duct indicates that TVOC sources, such as in the sixth-floor photocopying area, are dispersed quickly within the upper four floors. The level in the return duct for the office floors remained virtually unchanged from background levels, suggesting that relatively little VOC generation occurs on the lower floors. Since the upper and lower floors do not share common return ducts, little spread from the upper floors occurs.

HWC has not yet set an acceptable exposure range for TVOC, since the health effects of VOC in complex mixtures over the range of concentrations encountered in buildings are not well understood (HWC 1987). Well-defined exposure limits likely will not be established in the near future; efforts should thus be made to reduce the VOC levels in the building as much as possible or to eliminate the VOC sources.

Examination of the influence of building air change rate on TVOC concentrations levels was conducted in parallel with the CO_2 monitoring described above. Figure 10 shows the relationship between daily maximum VOC concentrations and air change rate for weekdays. Tripling the air change rate from 0.9 ach to 2.8 ach resulted in a TVOC concentration reduction of only 24% from 58 mg/m^3 to about 44 mg/m^3. This suggests that the best way to reduce VOC levels in the building is by source elimination or, where feasible, by supplying local exhaust.

Formaldehyde (HCHO) Formaldehyde concentrations were monitored on the roof and at 33 locations within the building using passive dosimeters. Three tests were conducted in the fall of 1987 and one in early 1988 under HVAC operating conditions of automatic mode, 100% outdoor air (mean air change rate = 2.8 ach), 75% OA (1.9 ach), and automatic mode (0.9 ach), respectively. Each five-day test (Monday to Friday) determined average HCHO levels during the exposure period, including evenings. Levels exceeding 0.025 ppm were observed at only three locations in the building, all occurring under the automatic HVAC mode. In Room 157, 0.042 ppm and 0.027 ppm HCHO were detected near the center of the occupied space and by a window, respectively. A level of 0.026 ppm was recorded near the center of the occupied space in Room 188 (first-floor library cataloging area). In Room 614 (sixth-floor photocopying area), 0.036-ppm and 0.046-ppm levels were detected at opposite ends of the occupied space, with the higher value occurring immediately above one of the six photocopiers in the area. Outdoor levels of 0.031 ppm observed in the first test appeared to result from painting and caulking of the building exterior that was conducted during the test. No strong correlations were observed between HCHO levels and air change rate.

To more precisely determine exposure levels to occupants during working hours, daytime HCHO levels in Room 614 were monitored via seven-hour midget impinger

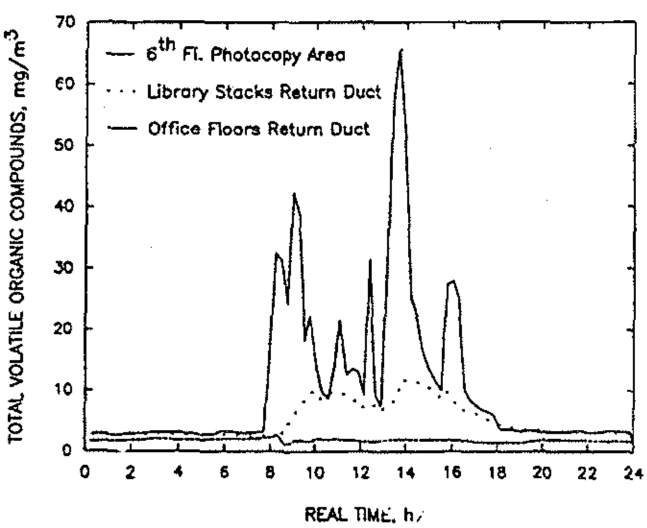

Figure 9 TVOC profiles for a typical weekday

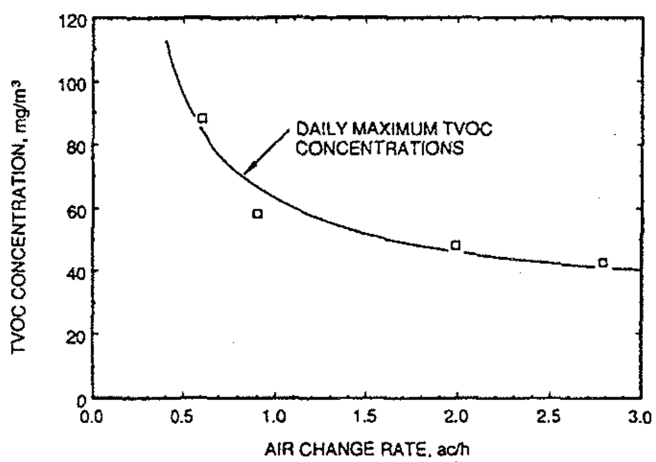

Figure 10 Daily maximum TVOC concentrations vs. air change rate for weekdays

sampling on four consecutive weekdays in February 1988. The first test was conducted under minimum fresh air HVAC operation and the rest on automatic mode. HCHO levels on the four days were 0.041, 0.021, 0.017, and 0.020 ppm, respectively.

The World Health Organization sets a "level of concern" for HCHO of 0.10 ppm (WHO 1983). HWC recommends that long-term exposure to HCHO should be limited, where possible, to levels below 0.05 ppm. While levels in the building were generally well below 0.05 ppm, this threshold was approached in both complaint areas (Rooms 157 and 614). Two possible HCHO sources were identified in Room 614: the photocopy paper, which may release HCHO when heated during the copy process, and the photocopy request forms used by the staff. These forms are printed on carbonless copy paper, several brands of which have been shown to contain large quantities of free HCHO (Wolkoff and Nielsen 1987). No HCHO sources were identified in Room 157.

Suspended Particulates Total suspended particulate (TSP) and respirable suspended particulate (RSP) levels were monitored at the breathing zone in 29 locations in the building. The complaint areas and all regions with particle-generating activities (e.g., smoking room, photocopying areas) were included. The impact of the HVAC systems on particle levels was also investigated. Monitoring was conducted under four HVAC operating conditions: the automatic damper control mode plus manual damper adjustment to give 100%, 75%, and 50% outdoor air.

Throughout the building, average RSP levels during working hours were generally below 2 $\mu g/m^3$. An exception was the smoking room (Room 87), where the average RSP concentration was approximately 11 $\mu g/m^3$, and levels up to 17.1 $\mu g/m^3$ were observed. Concentrations in the two complaint areas averaged 0.84 $\mu g/m^3$ for Room 157 and 1.16 $\mu g/m^3$ for Room 614. Peak RSP levels observed at these locations were 1.35 and 2.33 $\mu g/m^3$, respectively. Particle levels in Room 614 peaked at approximately 9 a.m. and 2 p.m. on working days. These periods corresponded with peak photocopying activity in the area.

For fine particulate matter (defined as less than 2.5 μm), ASTER and ALTER values of 100 and 40 $\mu g/m^3$ are specified by HWC. Particulate levels within this building were thus well within current guidelines.

Settled Particulates Sixty settled dust samples were collected in the building and examined using light microscopy. Very little dust was found accumulated on surfaces in occupied areas, even at locations not expected to receive regular cleaning. Wood pulp (fibers) was the most common component and likely originated from books and papers. Several samples contained paint particles. Most of these were collected on the ground floor, the source apparently being peeling floor paint in the basement mechanical room. Airborne glass or mineral fibers, which, due to their potential to cause cancer, are of concern (HWC recommends avoidance of inhalation or skin contact), were not observed in the building.

Biogenic Contaminants

The Bioaerosol Committee of the ACGIH (ACGIH 1987) recommends that sampling for contaminants of biological origin be conducted only when medical/clinical reports indicate the existence of illness resulting from bioaerosols (e.g., humidifier fever, hypersensitivity pneumonitis). Biogenic contaminant monitoring in this building was conducted without supporting clinical evidence since (1) a formal complaint of prolonged allergic reaction had been received and (2) the cooling tower is located near the outdoor air intakes of the HVAC systems. The initial inspection of the building included a search for potential sources of biological contaminants, such as standing water, moldy surfaces, or evidence of leaks and water stains. Bioaerosol sampling was conducted at locations throughout the occupied space of the building and within the HVAC systems (Unligil and Shirtliffe 1991). Liquid samples removed from the spray water reservoirs were analyzed for biological contaminants. Dust samples were microscopically examined for allergens.

While this investigation provided a quantitative analysis of the air and HVAC systems, little attempt was made to identify organism species. To augment this investigation, a detailed qualitative analysis of selected air and water samples was conducted by the Division of Biological Sciences of the NRC (Griffith 1988).

Air Samples More than 800 air samples were collected between summer 1987 and spring 1988 from locations inside and outside the building, and within the HVAC systems (Figure 11). The concentrations of fungi in the occupied spaces generally ranged from 80 to 200 colony-forming units per cubic meter (cfu/m³). The highest values observed were 494 cfu/m³ in the kitchen of the cafeteria on the second floor and 434 cfu/m³ in a first-floor janitor's closet. Exterior levels exceeded indoor concentrations during the summer, while the winter indoor and outdoor levels were similar.

Bioaerosol levels inside the HVAC systems were measured frequently between September 1987 and March 1988 (Figure 11). Table 1 shows that colony-forming units were generally much higher downstream of the water spray units. The spray unit in system 1 was particularly contaminated. Up to 10,600 cfu/m³ were detected, and upstream/downstream ratios ranged from 17 to 2,200. Additional testing of system 1 (Figure 12) provided further evidence that the water spray was the source of the contamination. Despite the high internal contamination, levels in the occupied space immediately at the supply registers from this system did not exceed 300 cfu/m³.

HWC states that it is not possible to recommend limits for biological agents in general. ACGIH, however, states that outdoor fungal spore levels during the growing season routinely range from 1,000 to 100,000 cfu/m³ of air and that, where outdoor air is the only source, indoor levels should be less than one-third of outdoor levels and should be qualitatively similar (ACGIH 1987). While the microbial aerosol concentrations in the main occupied areas of this building are relatively low (about 200 cfu/m³), the indoor-

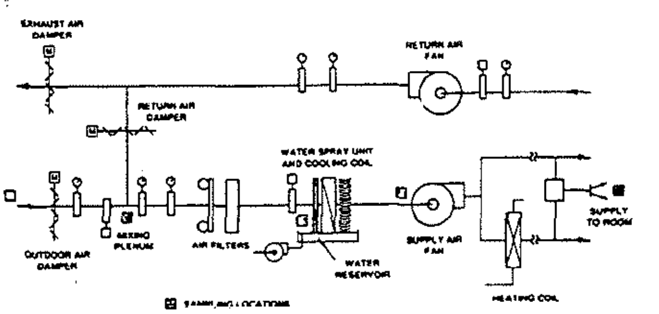

Figure 11 *Dual-duct HVAC system showing sampling locations for biological contaminants*

TABLE 1
Results of Microbiological Examinations of HVAC Systems

HVAC No.	Date 1987-88	Mixing Plenum	Water U'Stream	Spray D'Stream	Office Space	Water Reservoir	
		Concentration of Microorganisms in Air (cfu/m^3	(b)	(b)		Microorganism No./mL (c)	Endotoxin EU/ML (d)
1	9/24	53	34	578	188		
	10/27	103	22	638	196		
	1/28	78	91	7,500	219		
	2/03	63	69	10,600	236	121,000	1,200
	2/15	65	41	10,600	291		
	2/23	41	13	5,800	225		
	3/01	69	3	6,600	259		
	3/09	56	13	5,500	203		
	3/15	-	25	6,400	-		
2	9/24	6	25	188	84	310,000	120
	2/03	49	28	284	94		
3	9/24	175	19	69	230		
	2/23	56	0	106	91	0	1,200
4	9/24	78	69	38	325		
	1/28	34	59	550	44	40,000	60
	3/01	28	25	222	22		
	3/15	-	22	253	-		
5	9/24	31	13	59	240		
	2/15	56	0	25	13	11,000	300
6	2/23	31	38	156	63	221,000	300
7	1/28	72	81	106	69	2,400	60
8	10/28	38	13	100	40	140,000	1,200
	2/15	59	3	159	6		
9	3/01	31	28	494	109	250,000	6,000

(a) Tested with the water spray in operation, using RCS-Biotest Sampler with TSA medium incubated at 25°C. Values are averages of two strips exposed consecutively.
(b) The water spray is located downstream of the air filters: a prefilter and a HEPA filter.
(c) Examined using plate dilution technique with TSB medium.
(d) Limulus amebocyte lysate (LAL) test. Controls 24 and 60 endotoxin units (EU) per mL for ground and fourth floors, respectively.

outdoor species variability indicates that efforts should be made to remove the indoor sources (i.e., in the water spray systems).

Liquid Samples According to HWC, inhalation of endotoxins (compounds present in the cell walls of gram-negative bacteria) can induce an illness known as humidifier fever. Endotoxin levels in samples from HVAC spray water reservoirs were determined by a limulus amebocyte lysate assay. The concentrations in HVAC systems 1 through 9 were 1,200, 120, 1,200, 60, 300, 300, 60, 1,200, and 6,000 EU/mL (endotoxin units per ml), respectively. Tap water samples on the ground and seventh floors contained 24 and 60 EU/mL, respectively. These results suggest that the reservoirs of the water spray units in HVAC systems 1, 3, 8, and 9 were contaminated with endotoxin.

No established guidelines exist for estimating risk associated with endotoxin exposure or for estimating the amount of endotoxin that may be released to the air from contaminated water in HVAC systems. However, since the HVAC system water spray units were again identified as a contamination source, thorough cleaning of the systems was recommended.

Settled Dust Samples Examination of the dust samples described above revealed extremely low levels of plant pollens, fungal spores and hyphae fragments, bird fibers, and plant fragments.

SUMMARY

In general, the building, including mechanical rooms, was relatively clean. The level of dirt and dust was low on both office and library stacks floors. Very few plant pollens or fungal spores were detected in the indoor air or on the floor. No abnormally high concentrations of carbon monox-

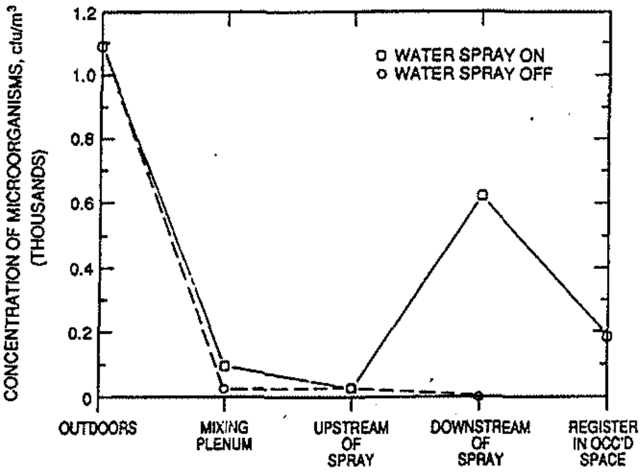

Figure 12 Effect of water spray on the microbial load of air (HVAC system 1)

ide, carbon dioxide, nitrogen oxide (NO_x), formaldehyde, suspended particulate matter, or total colony-forming units were detected in the office areas. The minimum outdoor air supply rate ranged from 0.4 to 0.6 ach, which translated to about 18 L/s per person. Air distribution within the building was good.

Several deficiencies were detected. It was found that the air in some areas was too warm and too dry, especially in the afternoon. The water reservoirs of several HVAC system water spray units showed heavy biological contamination. Concentrations of some microorganisms were abnormally high immediately downstream of the water spray unit in several systems.

At the first-floor complaint area, relative humidity (at 17% to 21%), was well below HWC guidelines. As a result, the thermal comfort conditions, both in the morning and in the afternoon, were outside the ASHRAE comfort zone. In addition, it was found that very little outdoor air was delivered directly through the HVAC system serving this area when the outdoor air damper was partially closed.

At the sixth floor, the total volatile organic compound (TVOC) concentration was consistently high. The TVOC level could not be substantially reduced by simply increasing the outdoor air supply rate of the whole building.

RECOMMENDATIONS

Based on the results, it was postulated that the occupants' complaints on the first floor might be caused by (1) a lack of outdoor air supply through the HVAC system serving this area because, under normal operating conditions, the outdoor air damper was never fully opened and (2) unsatisfactory thermal comfort conditions.

At the sixth floor, the occupants' complaints would likely be caused by higher-than-normal TVOC concentrations. The unsatisfactory thermal comfort conditions experienced in other areas and the contaminated water reservoirs in the HVAC systems might also contribute to the problem. The following remedial measures were, therefore, recommended for improving the air quality of the building as a whole and of the complaint areas:

The Building

(a) Check and adjust all thermostats and humidistats and install shades for the skylights.
(b) Conduct housecleaning and repaint the floors in the mechanical rooms.
(c) Clean and disinfect all water spray systems and replace existing water spray systems, if possible.
(d) Develop and apply a new preventive maintenance program.
(e) Check all HVAC systems for unintentionally closed dampers.

The First- and Sixth-Floor Complaint Areas

(a) Install separate exhaust air systems for copying machines.
(b) Balance airflows of main supply and return air fans for all systems (excluding system 3); install an outdoor air supply fan, if necessary.

Most of the recommendations have been implemented. More than a year has passed and no further complaints have been received.

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