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INDOOR AIR QUALITY ASSESSMENT IN AN OFFICE-LIBRARY BUILDING: PART I—TEST METHODS

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ABSTRACT

A detailed investigation of the indoor air quality (IAQ) 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, a decline in health, and prolonged allergic reaction.

Details of the study are presented in two papers. Part I describes the test plan and procedures, which, while developed specifically for this investigation, can be adapted for similar office building studies. Part II presents the study results and recommendations for remedial measures for this building.

INTRODUCTION

As concern for air quality in office buildings has grown, so, too, has the demand for its assessment. Evaluation is, however, often hampered by the diverse and nonspecific symptoms reported by office staff and the fact that established evaluation criteria for industrial exposures are not generally applicable to office environments (NIOSH 1987). Although standards such as *ASHRAE 62-1989* (ASHRAE 1989) provide guidelines for outdoor air requirements and exposure limits for office buildings, the information is far from complete. Furthermore, where standards exist, accepted measurement techniques for determining compliance are generally lacking. Thus, modification of existing methods—and/or development of new ones—is often required.

This is the first of two papers describing a detailed indoor air quality investigation of an eight-story office/library complex, the main objective of which was to determine the cause(s) of repeated complaints by occupants dating back to 1981. This paper presents the test methods; a second paper discusses the test results (Shaw et al. 1991).

TEST BUILDING

The building is a fully air-conditioned eight-story office/library building in which the first four floors contain offices and the remaining four house library stacks. The floor area of each of the lower three floors is about 4,800 m^2 and that of each of the upper five floors is about 2,400 m^2. 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 with a separate ventilation system. 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. The photocopiers were vented into the floor space.

The building has nine air-conditioning systems (Figure 1). Systems 1 and 2 are all-air, two-deck systems that serve

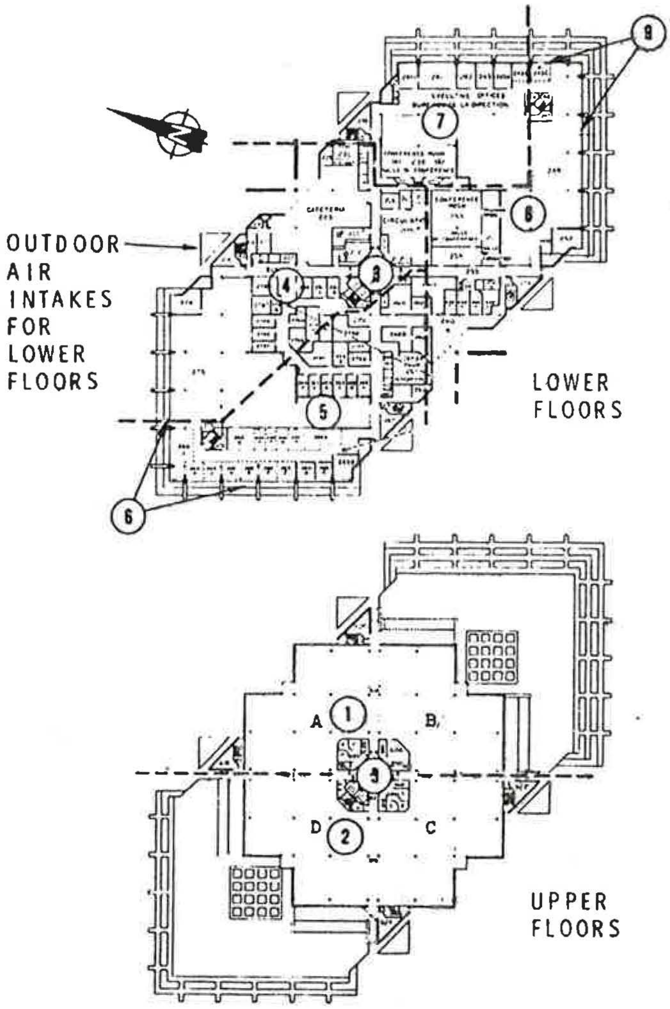

Figure 1 *Typical floor plans showing the HVAC systems*

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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 these 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 that 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 (Figure 1).

AIR-QUALITY-RELATED COMPLAINTS AND PREVIOUS INVESTIGATIONS

At the request of the building management, no occupant survey was conducted. The nature and extent of occupant complaints could thus be discerned only from interoffice memoranda supplied by the administration. These documents included a formal complaint of prolonged allergic reaction and decline in health by an employee working in the southern and southeastern areas of the first floor. Several verbal complaints of stuffy air, headaches, and eye irritation were received from employees working in the fifth- and sixth-floor photocopy areas.

In an attempt to determine the cause(s) of the complaints, two pilot studies were initiated. In the first, conducted in 1981, CO_2, CO, ozone, and total suspended particulates on the ground, second, and third floors were measured for a two-week period. As the measured concentrations were all within the limits recommended by *ASHRAE Standard 62-1981* (ASHRAE 1981b), no causal agents could be identified and, therefore, no remedial measures were recommended.

A second investigation, conducted in 1986 after complaints continued, recorded concentrations of total volatile organic compounds (TVOC) and fungal spores in addition to the contaminants measured in the 1981 study. Dust, liquid, and air samples were examined for principal components. TVOC concentrations in the complaint areas on the first and sixth floors exceeded values found to cause complaints (Molhave et al. 1986). The main TVOC source was identified as the exhaust gas from liquid toner, transfer process photocopiers. The study was not, however, extensive enough to rule out other possible causes of the occupants' complaints. A third investigation, the subject of this report, was carried out between March 1987 and August 1988.

DEVELOPMENT OF ASSESSMENT PLAN

The symptoms described by the employees, the failure to identify the causal agents in the two previous studies, and the lack of clinical evidence of known building-related illness all suggest that the indoor environment of this building resembled that of "sick building syndrome" (ACGIH 1987; WHO 1983; Finnegan et al. 1984; Hodgson et al. 1986). An assessment plan was developed accordingly (Shaw 1988a,b). The 10-point plan (see Appendix A for a brief description) included a thorough check of the heating, ventilating, and air-conditioning systems. Other tasks included studying the building's use and occupancy, identifying and measuring the air contaminants involved, and establishing a basis for remedial measures. This plan is designed for a study team consisting of an engineer, an HVAC technician, and several individuals familiar with industrial hygiene evaluation techniques.

METHODS OF MEASUREMENT

The air quality examination was divided into three main sections: the design and operational characteristics of the HVAC systems, the levels and sources of chemical and particulate contaminants, and the levels and sources of contaminants of biological origin. Methods for each are discussed below.

HVAC Systems

The performance of the HVAC systems was assessed on the basis of air change rates, air distribution patterns, thermal comfort conditions in the occupied areas, and problems related to HVAC design, installation, and operation. The methods of measurement used are discussed below.

Air Change Rates Air change rates were measured using the tracer gas decay method. The HVAC systems were set according to predetermined test conditions (for example, the outdoor air dampers were set at their minimum opening positions when checking the minimum ventilation rate). A small amount of SF_6 tracer gas was injected directly into the supply air ducts of systems 1, 2, 6, and 9 (these systems were selected to ensure that SF_6 was injected directly into each story at well-distributed locations). The total amount of tracer gas required was calculated from the equation:

$$m = V \cdot C_t$$

where

m = amount of tracer gas
V = building volume
C_t = maximum concentration.

The maximum tracer concentration required depends on analyzer sensitivity. For the gas chromatograph/electron capture detector employed in this study, a concentration of 50 ppb was selected. With a building volume of approximately 80,000 m^3, the total quantity of pure SF_6 required was:

$$\begin{aligned} m &= 80{,}000\ m^3 \cdot 1{,}000\ L/m^3 \cdot 50 \text{ parts } SF_6/10^9 \text{ parts air} \\ &= 8 \times 10^7\ L \cdot 50 \times 10^{-9} \\ &= 4\ L \text{ pure } SF_6. \end{aligned}$$

After injection, about one hour was allowed for mixing of the tracer. An automated system was then used to collect samples from return ducts at each floor. Samples from each location were continuously pumped via 4.8-mm-ID plastic tubing to a multi-position valve that automatically sent the samples, one after another, to the gas chromatograph for analysis.

To evaluate mixing of the tracer gas with the indoor air, additional samples were collected manually at 10-minute intervals from two locations on each floor as follows. Just prior to the sampling time, a 60-mL syringe was purged twice with air at the test location. At the designated time, 50 mL of air was collected in the syringe exposure levels were, in effect, average values over a single sampling duration, while "average" exposures were the mean value of the test period.

For tests of the HVAC systems, the sensor sampling inlet was extended with streamline copper tubing to positions immediately in front of supply air registers. Supply air particle levels were thus determined for automatic HVAC operation and under conditions of approximately 100%, 75%, and 50% fresh air. In addition, samples of the filter media (roll-type and HEPA) were collected from the HVAC systems and examined by light microscopy.

Settled Particulates Settled dust samples were collected from hard, glassy, or polished metal surfaces inside the building using tweezers or transparent adhesive tapes. Microscope slides coated with glycerine were left for eight weeks at various locations to collect fresh samples. Sample examinations for components were made using bright field and polarized light microscopy.

Biogenic Contaminants

Air and water samples from locations inside and outside the building were examined for biological contaminants (Unligil and Shirtliffe 1991). The draft guidelines produced by the ACGIH Committee on Bioaerosols were closely followed (ACGIH 1987). Special attention was given to the various compartments of the HVAC systems. Settled dust samples from high- and low-traffic areas and from air filters were also examined for biogenic air contaminants including allergens such as plant pollens, fungal spores, and hyphal fragments.

Air Samples Two techniques were employed for collection of microbial aerosol samples. Both involved collection of samples on nutrient agar, incubation of the exposed media at 25°C, and subsequent counting and identification of colonies. The principal difference in the methods lay in the collection procedure. The first used centrifugal air samplers (flow rate: 40 L/min; sampling time: 4 min), while the second involved settling onto 100-mm-diameter by 15-mm-high petri plates. The settling technique was employed in the library stack areas of the building. Rose bengal-streptomycin-agar (RSA) was used as the medium for yeasts and molds, and tryptic soy-agar (TSA) was used for the total count (i.e., yeasts, molds, and bacteria).

For examinations of the HVAC systems, the centrifugal samplers were used to take air samples outside the outdoor air supply register, upstream of the air prefilters at the mixing chamber, upstream of the water spray unit, at the intake of the supply air fan just downstream of the water spray unit, and near the supply air registers (Figure 5). To determine the effect of aerosols generated by water spray units, sampling was conducted with the water spray unit both on and off.

Settled Dust Samples Samples of settled particulates were examined for the presence of allergens (see above for methods of collection and analysis). Lactophenol-containing crystal violet or cotton blue was used as a fixative and mounting medium for the detection of fungal hyphae.

Liquid Samples Samples from the reservoirs in the HVAC spray water systems were analyzed for endotoxin contamination levels. Endotoxins are constituents of the cell walls of some bacteria.

DISCUSSION

The tracer-gas decay technique was chosen for measuring air change rates because it can be conducted by teams without expensive tracer gas detectors, since the manually collected tracer gas samples can be sent to a laboratory for analysis. This technique is also suitable for conducting air distribution tests and tracing the movement of contaminants generated at a local source in tall buildings. For a typical 10-minute sampling interval, one person can easily take samples from five key locations on a single floor.

In checking air distribution within the building, no attempt was made to measure ventilation effectiveness, since this remains an active research topic with a confusing range of definitions. Individual researchers have not always been consistent with terminology used in its description, and different authors have occasionally used different expressions to represent the same parameter (AIVC 1987).

A combination of mechanical drawing analysis, visual inspections, and spot measurements is needed to detect installation and operational problems in HVAC systems. For example, an inspection of one of this building's supply air systems indicated that the system performed well when it was operated at 100% outside air (i.e., outdoor air damper fully open). However, the outdoor air supply rate was found to be almost zero when the damper was partially closed. The problem was caused by a combination of high fluid resistance in the supply air duct, an oversized return air damper, and a powerful return air fan.

When sampling lines are used to bring samples to a central location for quantification of chemical contaminants, a check should be made to ensure that the lines do not act as a sink or source through absorption or desorption. This can be checked by analysis of calibration standards directly at the instrument through various lengths of sampling line. For CO and CO_2 measurements, the analytical differences were less than 1% for lengths of PVC sampling tube of less than 150 m. Based on the same criterion, the maximum length of tube used for collecting THC samples was determined to be about 60 m.

According to the ACGIH Bioaerosols Committee, air sampling for biological contaminants should only be initiated after medical or clinical assessments indicate the existence of illness that is likely due to bioaerosols (ACGIH 1987). Although in this study no positive evidence existed for workplace-related illness due to biological contamination, bioaerosol sampling was conducted because (1) it was noted that the cooling tower exhaust location is near the outdoor air intakes of the HVAC systems, and (2) there was a formal complaint of prolonged allergic reaction.

SUMMARY

This paper describes the measurement methods undertaken to implement a plan for assessing the indoor air

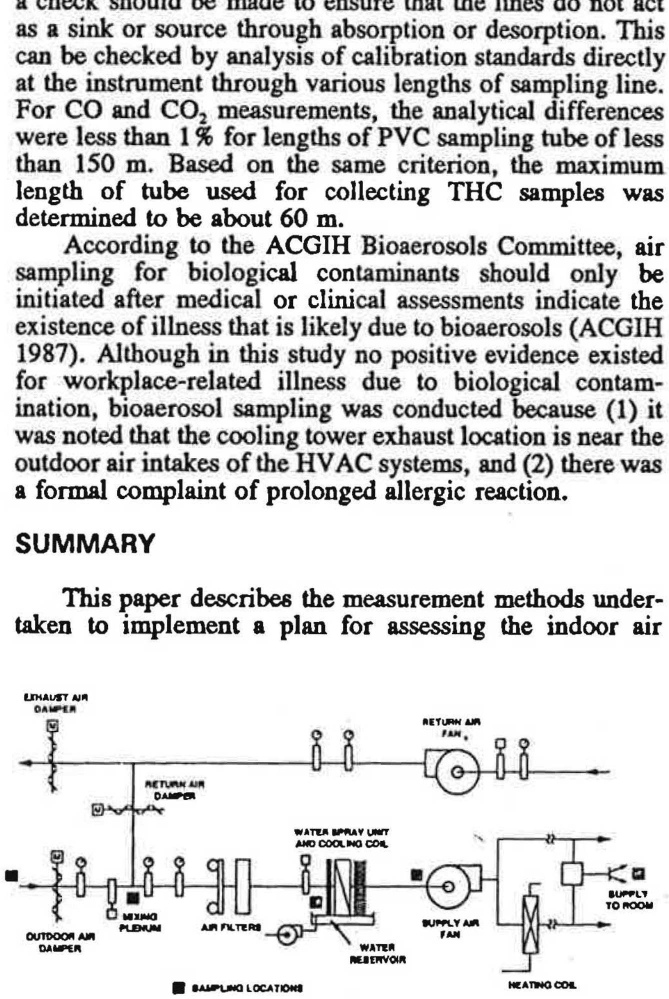

Figure 5 *Dual-duct HVAC system showing sampling locations for biological contaminants*

quality of an eight-story office/library building. Included are techniques for assessing the performance of HVAC systems, measuring chemical and biological contaminants, and establishing a correlation between air change rate and CO_2 concentration. Both the plan and test methods were applied successfully on the test building. The methods used for measuring air change rate and air distribution patterns have also been applied successfully in other buildings.

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APPENDIX A

PROPOSED PLAN

The proposed plan developed for assessing the indoor air quality consists of 10 tasks. The details are discussed below.

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 the occupants' concerns and a study of the building drawings, with particular attention to the HVAC systems. An occupant survey can be conducted using, for example, the NIOSH Indoor Air Quality Questionnaire. 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 are 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 airflow patterns and detect possible short-circuiting between supply and return airflows. 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 analyze the information obtained in Tasks 1 and 2 so as to develop a sampling and measuring strategy for an in-depth study, if necessary. An in-depth investigation should include Tasks 4 through 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 measurements 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 give 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 at 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 the 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 62-1989*. The minimum air change rate of a building can be determined by conducting four or five tests under warm weather and calm wind conditions (i.e., outdoor air temperature higher than 15°C and windspeed lower than 20 km/h) and 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 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 reenters the building and how fast a contaminant (or the outdoor air) spreads from its source (point of entry) to other areas. The reentrainment 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. The 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 tracer gas concentrations with time at the injection location and also at several other locations on each floor. The faster the concentrations of 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 from these areas to the surrounding rooms 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 analyzing the 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.

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 Relationship between Contaminant Concentrations and Air Change Rates

The objective of this task is to establish the relationship between concentrations and air change rates for selected chemical and biological contaminants. These and established standards such as *ASHRAE 62-1989* can be used to determine the amount of outdoor air required to maintain the contaminants below prescribed limits if source removal is not practical. It also can be used to estimate the amount of outdoor air required to cope with any changes in certain contamination loads.

Task 9—Final Review

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.

Task 10—Report

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