#5576

Indoor air quality evaluation of a new office building

The effects of the building's design, construction and operation on its thermal and environmental performance will be evaluated

By *Richard A. Grot, Ph.D., Alfred T. Hodgson, Joan M. Daisey, Ph.D., and Andrew Persily, Ph.D.*
Member ASHRAE

An evaluation of the thermal and environmental performance of a new federal office building in Portland, Oregon, was performed by the Center for Building Technology, National Institute of Standards and Technology (NIST). This evaluation is part of a research effort to develop methods for evaluating buildings with advanced technology during the pre-occupancy and early occupancy stages.

The procedure used for this evaluation was to install in the new office building a diagnostic center capable of monitoring important environmental parameters. The measurements included: air infiltration and ventilation rates; building envelope tightness; interzone air movement; detection of envelope thermal deficiencies; envelope thermal resistance; and the levels of indoor contaminants.

The indoor contaminants measured include carbon dioxide (CO_2), carbon monoxide (CO), respirable particulates in the 0.3-10 micron range, formaldehyde, radon and volatile organic compounds (VOCs) that could be emitted either by the new building materials and furnishings or the activities of the building occupants.

There were more than 100 monitoring points (see *Figure 1*) installed in the building's interior space, HVAC systems and underground parking garage. Many measurements were made in real-time.

Building description

The new office building was constructed during 1986–87 and occupancy began in August, 1987. It is a seven-story office building with a one-story basement and a two-and-one-half story underground garage (see *Figure 1*). Attached to the building are a dining room and kitchen. The penthouse contains a mechanical equipment room that serves the first through seventh floors.

There are three main HVAC systems that serve the east, center and west cores of the building, respectively. These three variable air volume (VAV) systems have a total capacity of approximately 300,000 cfm (140 m^3/s), or about three air changes per hour. Each HVAC system has one return fan, two cold supply fans and a hot supply fan.

On the B-1 occupied basement level, there are four air handling systems that serve various sections of the basement. The B-1 level also contains the loading dock. Above and to the north of the loading dock is an air handler system for the dining room. In the underground garages, there are four exhaust fans that are activated when CO levels in the garage reach 50 ppm.

The building's occupied area is approximately 495,000 sq ft (46,000 m^2) and has a volume of about 6.4 million cu ft (180,000 m^3). The garage is connected to the occupied space by several stair and elevator shafts. The building's interior plan features an open architecture, with each occupant having a space enclosed by 5 ft partitions. On most floors, there are enclosed offices for supervisors and enclosed conference rooms that do not have separate air handling systems. The second floor contains a computer facility. The building is occupied by approximately 2,000 office workers.

Measurement methods

A diagnostic center was installed in the building during the later stages of construction. A schematic of this diagnostic center is shown in *Figure 2*. Its instrumentation[6] was designed to measure automatically the air infiltration and

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ventilation rates of various parts of the building, internal temperatures and humidity, exterior temperature, wind speed and direction, indoor and outdoor levels of carbon dioxide and carbon monoxide, and indoor levels of respirable particles in six size ranges (0.3-0.5, 0.5-0.7, 0.7-1.0, 1-5, 5-10 and >10 microns). In addition, check measurements were made of the concentrations of formaldehyde, radon and VOCs.

The air exchange rates were measured using the tracer gas decay technique with an automated measuring system. This system has been used previously to provide continuous measurements of building air exchange rates in office buildings.[2] For these measurements, the system injects sulfur hexafluoride (SF_6) into the supply fans every two or three hours, allows the tracer gas to mix, and then monitors the decay in tracer concentration at several locations within the building.

The sampling locations were placed both in the interior space and in the air handling systems. In general, each air handling system had three air sampling locations: one downstream of the intake fans; one upstream of the intake fan; and one in the return fan. These samplers were connected directly to the diagnostic center through 5/8-in. OD nylon or polyethylene tubing. Each air handling system had two locations for injecting tracer gas (one upstream and one downstream of the supply air fans).

Similar sampling points were located on each level of the underground garages. In addition, samplers were placed in the exhaust air of the garage's four exhaust fans. Samplers were also installed at two locations outdoors on the roof and at two locations outdoors at street level.

The pollutant levels were measured using a variety of techniques. Carbon monoxide and carbon dioxide were measured with an automated system employing infrared absorption analyzers for determining concentrations and a microcomputer to switch among the sampling locations and to record data. This system automatically monitored the CO and CO_2 concentrations at 10 locations in the building, each location being monitored once every 10 minutes.

Particle concentrations were monitored with a light-scattering particle counter that determines particle concentrations in six different size ranges (0.3-0.5, 0.5-0.7, 0.7-1.0, 1-5, 5-10 and >10 microns). Cumulative particle counts were recorded on a disk by a microcomputer-based data acquisition system.

Formaldehyde concentrations were measured with a passive monitor based on absorption onto a sodium bisulfite-treated filter and analysis by the chromotropic acid colorimetric method. These passive samplers yield average formaldehyde concentrations for periods from five to seven days.

Radon concentrations were measured with charcoal canisters for periods of about three days. A working level monitor was used to obtain hourly measurements of radon progeny levels.

Volatile organic compounds were measured using active sampling on a polyphenylene oxide and/or charcoal with analysis by a gas chromatograph/mass spectrometer. Air samples were collected on multisorbent samplers containing three sorbent materials in series: a polyphenylene oxide, a carbon molecular sieve and activated carbon. Samples were analyzed using a thermal desorption and sample concentrating device, a capillary gas chromatograph equipped with an on-column cryogenic focusing device, and a mass-selective detector.

Following thermal desorption, a portion of the sample was split off to a flame-ionization detector to measure total organic carbon. The mass-selective detector was operated in scan mode for qualitative analyses and in selected ion mode for quantitative analyses.

Summary of results

A complete summary of the results of the evaluation may be found in Grot[3] and Hodgson.[4] The building ventilation and air infiltration rates are shown in *Figure 3* as a function of inside-outside temperature difference. Building ventilation rates (open diamonds in *Figure 3*) are between 0.4 to 2.2 air changes per hour during periods when the building is occupied, with the most typical values being about 1.0 to 1.2 air changes per hour. The extreme of 0.4 occurs during extremely hot summer conditions or extremely cold (for Portland, Oregon) winter conditions.

For comparison, the new ASHRAE *Standard 62-1989*[1] requires a ventilation rate of 20 cfm per person for office buildings. This is equivalent to 0.8 to 0.9 air changes per hour if the building is occupied at a density of one person per 135 sq ft.

The building air leakage (uncontrolled air exchange when the HVAC fans are off during unoccupied hours; solid squares in *Figure 3*) is between 0.2 and 0.4 air changes per hour. Although this building was designed to be energy efficient, these values indicate that the exterior walls are not tight by what would be considered typical of U.S. office buildings. (Note: The surface-to-volume ratio of an office building is about 1/6 of a home. Therefore, the walls of this building are equivalent to the walls of a house with an air leakage of about 1.2 to 2.4 air changes per hour; very loose.)

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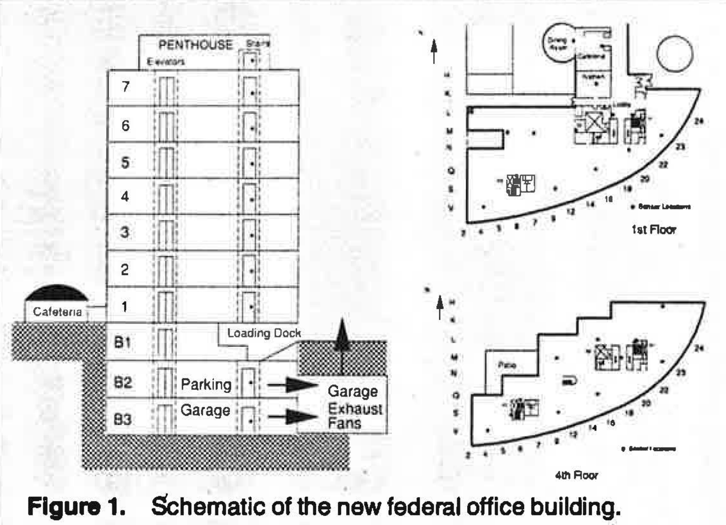

Figure 1. Schematic of the new federal office building.

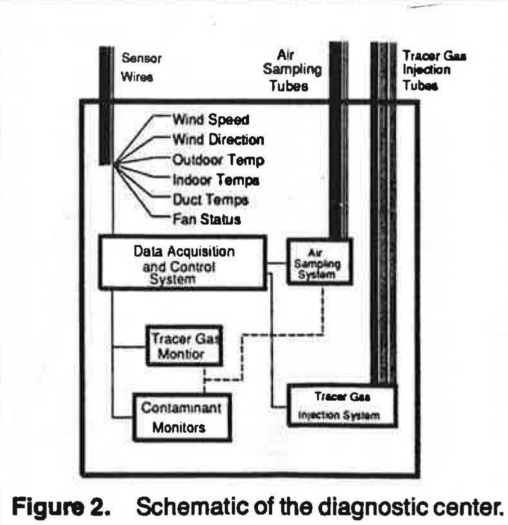

Figure 2. Schematic of the diagnostic center.

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Carbon dioxide concentrations were measured every 10 minutes at 10 locations in the building for a period of two years. *Figure 4* shows the maximum daily CO_2 level as a function of air exchange rate. Carbon dioxide levels are seldom over 600 ppm on a building average and only a few times over 1,000 ppm at any location. (*Standard 62-1989* proposes a maximum level of 1,000 ppm; complaints from building occupants begin to occur when levels exceed 600 ppm.)

A closer examination of the hourly CO_2 levels in the building shows that the obtainable levels are never at steady state and usually have two daily peaks—one around 11 am and the other around 3 pm. It is also shown by the values of the constants of the fitted curve in *Figure 4*. The value of 100 is approximately 1/3 of the expected equilibrium value based on the building occupancy.

A detailed examination of the SF_6 and CO_2 data shows that the air handling system can easily control the amount of air required for the building. The outdoor air is well distributed and there is little or no evidence of short-circuiting of the outdoor supply air or poor mixing due to operation of the VAV air handling system.

In the summer and warmer periods of the fall and spring, the typical operational mode runs this air handling system at 100% outdoor air from early morning to a point in the day when the outside temperature reaches about 79°F (26°C), at which time the system is run at between 10-20% outdoor air. Last winter, an economizer mode of operation was used in which the amount of outdoor air was determined by the building's cooling requirements.

The CO concentrations were measured at 10-minute intervals in the underground garage, loading dock, elevator lobbies, stairwells and various interior locations. *Figure 5* shows the high CO levels occurring in the elevator lobby of the sixth floor.

For the building as a whole, high interior CO levels were usually associated with high exterior CO levels. However, certain areas near elevator shafts and stairwells had episodic elevated CO concentrations that were much higher than the building average.

An examination of CO data showed that the incidents of excessive CO levels (greater than 10 ppm) in the upper building were due to the air flow from the underground parking garage toward the elevator shafts and stairwells. It seems that the automated sensors in the garage (although activating the exhaust fans as designed when the CO level in the garage exceeds 50 ppm) will not prevent the transport of CO up the elevator shafts and stairwells in extreme weather conditions when the stack effect is strongest. Once the garage exhaust fans (at least two of the four) were operated continuously during occupied hours, the CO level in the office space never exceeded 5 ppm.

Another area of occasional high CO concentrations was the return air being recirculated to the dining room. The air handler for the dining room is located on a platform above the loading dock. During periods of excessive vehicular traffic on the loading dock, CO entered through leaks in the return ducts.

The measured radon levels in the building are below 0.007 working levels (the ASHRAE level is 0.027 working le\ the EPA action level is 0.02 working le\ as measured in terms of the equival radiation impact of the radon daugh and less than 1.2 pCi/l (the ASHR recommended level is 4 pCi/l; the E action level is 4 pCi/l) in terms of amount of radon gas. The radon level the low garage levels are higher than th of the upper floors.

It is interesting that the upper flo of the occupied space have consister higher radon levels than the lower abc ground levels. This can be attributed to fact that air flows into the elevator sh and stairwells on the lower levels and ou these shafts on the upper levels.

Respirable particle counts in the size ranges (0.3-0.5, 0.5-0.7, 0.7-1.0, 1 5-10 and >10 microns) were measu every 10 minutes on the fourth floor. T levels of the fine particles in the 0.3- micron range remain fairly constant a show little hourly or daily variation. T three ranges of 0.5-0.7, 0.7-1.0 and microns have much more pronounced v iations. The two ranges greater tha microns are not considered respirable.

Excessively high particle levels in 0.7-1.0 and 1-5 micron ranges were served after the parking garage was clear with street-type sweeping machines. T building maintenance staff reported t all filters in the air handlers had to replaced after the sweeping.

In general, the respirable parti levels in the building (particles of a size l than 3 microns) are in the 10 to 15 milli particles per cubic meter range, which typical for office buildings without sm ing that we measured (data from a limi

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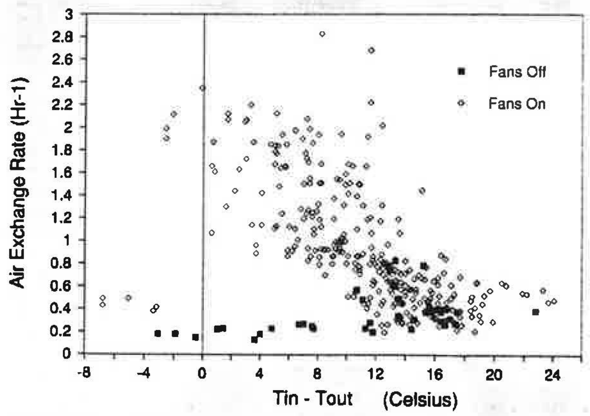

Figure 3. Air exchange rate versus inside-outside temperature difference. (Note: Fans-on data are ventilation rates; fans-off data are infiltration rates.)

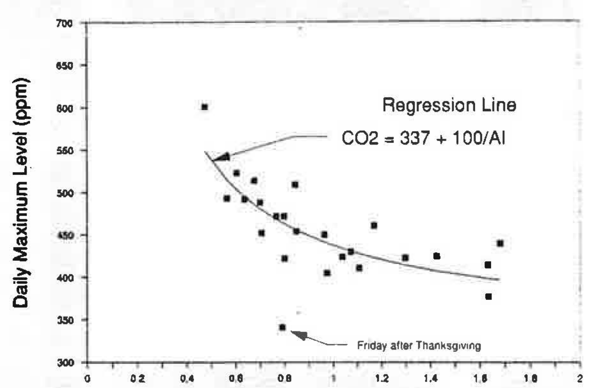

Figure 4. Carbon dioxide level versus ventilation.

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number of buildings). It is difficult to compare the measured particle levels with established standards because the standards are given in micrograms per cubic meter and there is great uncertainty in converting from particle counts per cubic meter to micrograms per cubic meter without more detailed analysis of the composition of the particles present in the building.

The formaldehyde level was measured in August 1987 when new furniture was being installed and the occupants were moving into the building. The carpeting (a removable type of carpet squares with a pressure sensitive adhesive) was installed from April through July in most parts of the building. The measurement results are shown in *Figure 6*. The measured formaldehyde levels are less than 0.056 p[illegible] (the ASHRAE level is 0.1 ppm; complai[illegible] begin at 0.06 ppm; outside levels are ty[illegible] cally 0.04 ppm). There is little or no outga[illegible] ing of formaldehyde from the furnishi[illegible] and carpets.

The last class of pollutants measu[illegible] was the volatile organic compour[illegible] (VOCs). Measurements were made on f[illegible] different occasions: August 4, 1987, wi[illegible]

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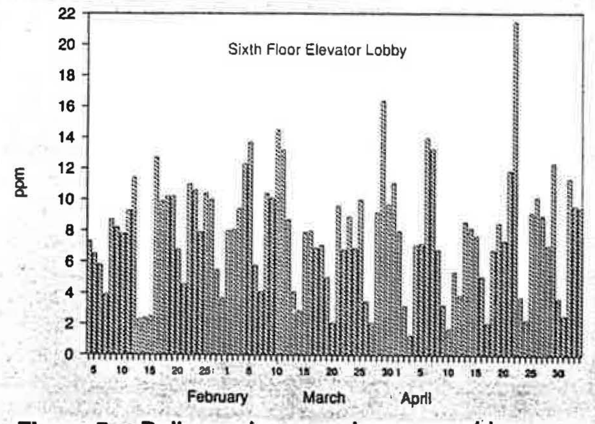


Figure 5. Daily maximum carbon monoxide concentrations in 6th floor lobby for months of February to May.

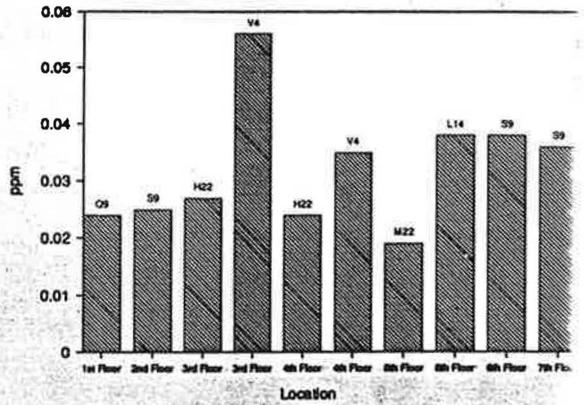
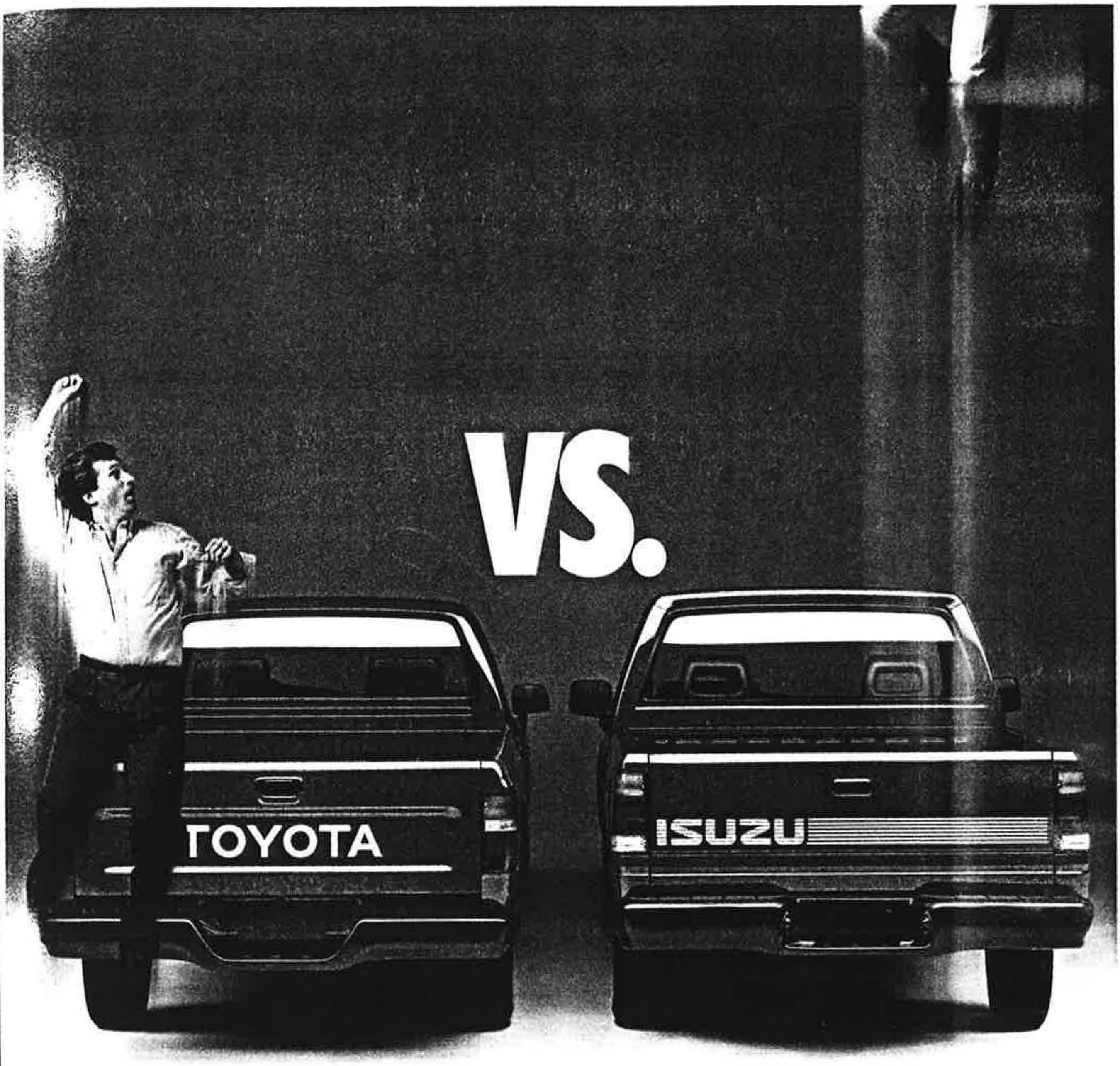


Figure 6. Formaldehyde levels in building.



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The First Annual IAQ Conference & Exposition

The First Annual IAQ Conference & Exposition will be held at the Tampa Convention Center in Tampa, Fla., April 30 - May 2, 1992. The conference will consist of three full days of technical seminars and exhibits.

A unique event, this conference and exposition will be the first to focus on *solutions* to IAQ problems stemming from complex HVAC systems in commercial buildings. Speakers will present a practical, hands-on approach to solving IAQ problems through proper care, maintenance, and service of HVAC systems.

These methods and techniques will be presented in terms that building owners and managers, engineers, and contractors can understand and readily implement.

The conference is sponsored by the National Coalition on Indoor Air Quality (NCIAQ). NCIAQ is a non-profit organization consisting of trade associations with active involvement in IAQ diagnosis and problem mitigation. Presently, the Associated Air Balance Council (AABC) and the National Air Filtration Association (NAFA) are members of NCIAQ. Other associations with members involved in hands-on IAQ service industries are anticipated to join NCIAQ in sponsoring the conference.

CALL FOR PAPERS

Those wishing to submit a paper for presentation should submit an application and abstract of 200 words or less, no later than September 1. Presentations should be limited to 30 to 45 minutes in length. Interested parties should call or write the National Coalition on Indoor Air Quality for an application for submittal. Final versions of the selected papers must be received no later than Nov. 1, 1991.

Topics for presentation may include, but are not limited to, the following:

Air Testing & Balancing
Air Duct Cleaning
Air Filtration
IAQ Investigations
IAQ Case Histories
System Commissioning
Contamination Assessment
IAQ Building Maintenance
Air Exchange Rates
Air Sampling Techniques
Tracer Gas Technology
Application of Instrumentation
Air Cleaning Equipment
Ventilation Effectiveness
HVAC Diagnostics
Troubleshooting
HVAC Controls

CALL FOR EXHIBITORS

Exhibit space is available to companies interested in marketing their equipment, products, or services to building owners, engineers, and contractors involved with IAQ mitigation. The First Annual IAQ Conference & Exposition is designed to attract building owners and managers, professional engineers, contractors, and building maintenance personnel. In all, more than 2,000 persons are expected to attend.

The equipment and services exhibited may include, but are not limited to:

Air Filtration Products
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While there is no limit on the amount of space each exhibitor may reserve, there is a limit on total exhibit space for the show. Thus, space will be allocated on a first-come, first-served basis.

To reserve a space, call or write NCIAQ for an exhibitor prospectus.

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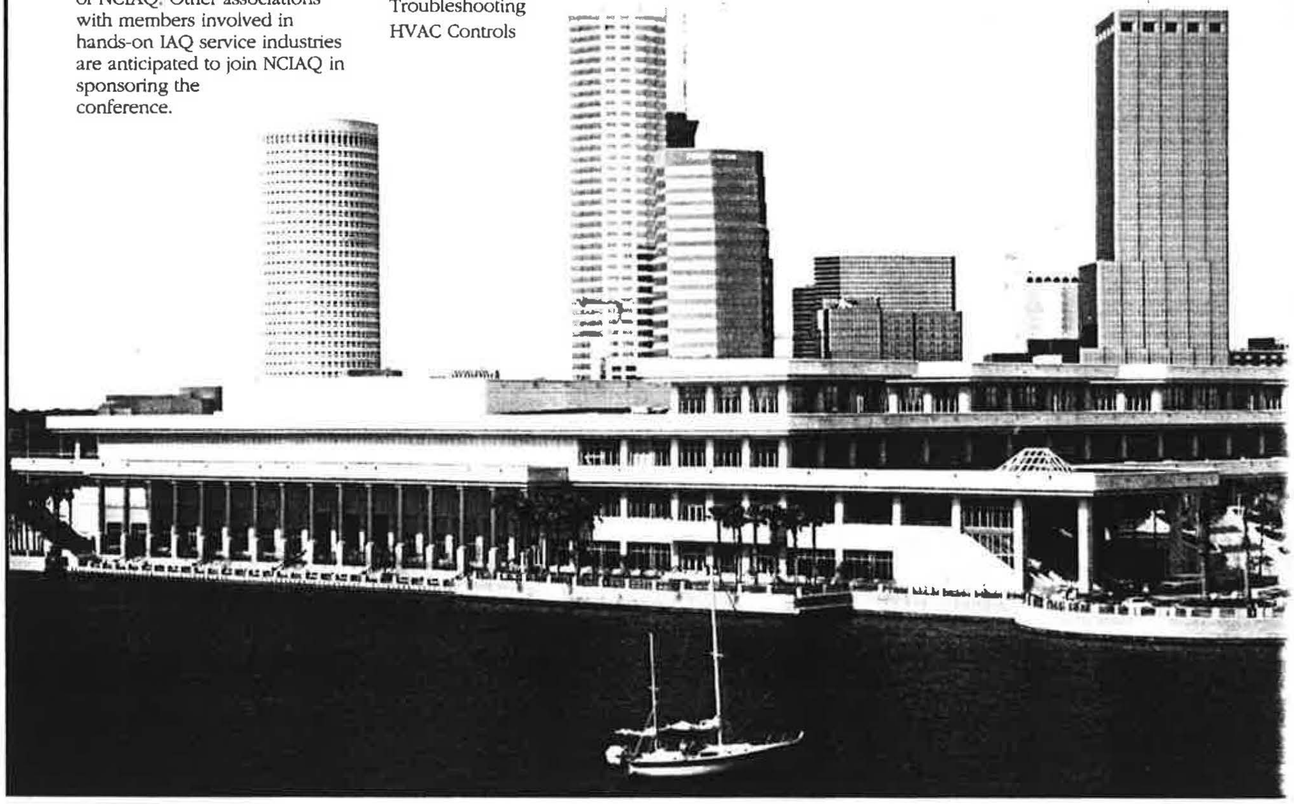

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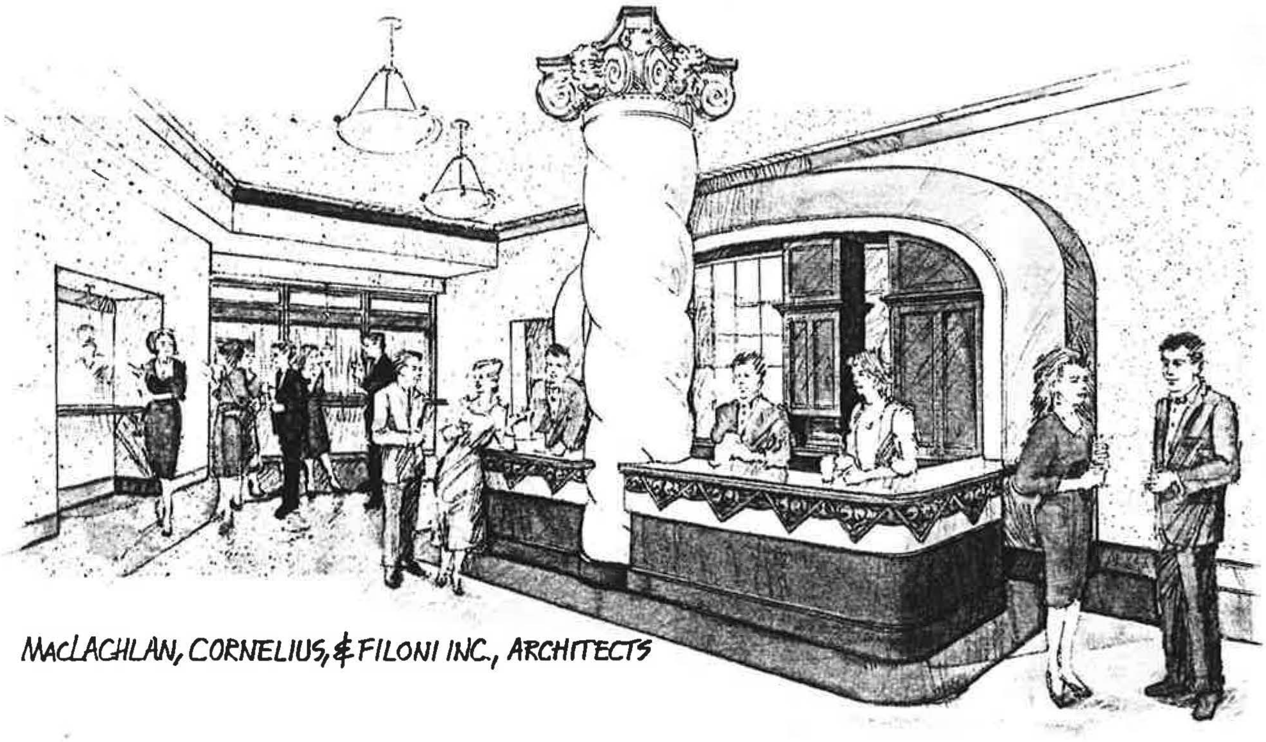

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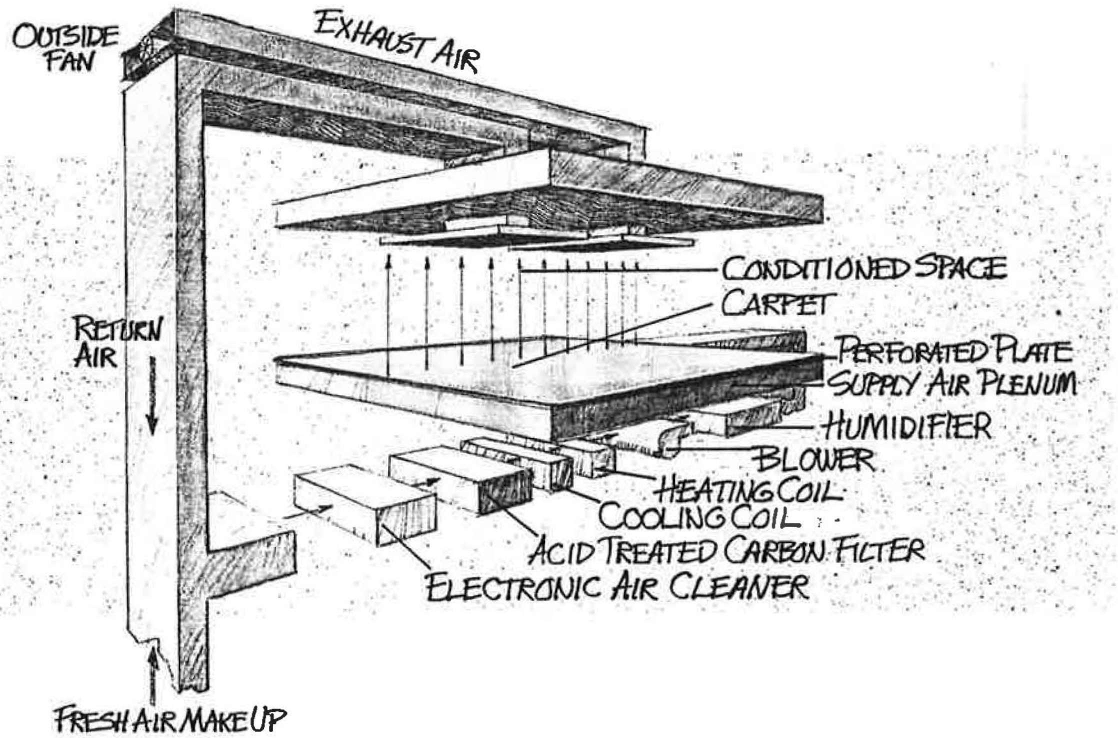

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the occupants were moving into the building; October 14, 1987; January 13, 1988; and October 28–31, 1989. On each date, the building was operated with four distinct air exchange rates (0.5, 1.36, 0.24 and 1.99 changes per hour) due to the prevailing exterior weather conditions.

Figure 7 shows the effect of building ventilation rate on the total VOC concentration. The curve represents the predicted level using the source strengths estimated from the VOC levels and the air change rates. The source strength of total VOC was remarkably constant over the 17-month period between the first and last measurements.

We measured and identified 37 VOCs in the interior building space (see *Table I*). There were five oxygenated compounds, six halogenated compounds, 16 alkanes, six cycloalkanes and alkenes, and five aromatic hydrocarbons. All are at levels less than 1/1,000 of the OSHA standard environmental levels for industrial work spaces. (Note: The ASHRAE standard recommends that, for indoor air quality, the level be not more than 1/10 of OSHA permissible exposure limits.)

The largest amount of VOCs is concentrated in the alkane class (C_{10} to C_{12} branched decanes and undecanes). These are not particularly irritating compounds and there are no OSHA permissible exposure limits for these substances. However, very limited studies by Molhave[5] indicated that many complaints will occur when the total levels of VOCs exceeds 5 mg/m^3. It has been recommended by researchers[9] at EPA Research Triangle Park that a prudent target level for total VOCs be 1 mg/m^3 (Seifert[8] proposes 0.3 mg/m^3).

All three measurement sets made in the building were greater than 1 mg/m^3 and the building exceeded 5 mg/m^3 when the ventilation rate was below 0.5 air changes per hour. We tested the major building components and furnishings for outgassing and these are not the sources. Although always operating the ventilation system at 100% outdoor air would keep the levels near 1 mg/m^3, identifying and limiting the sources is a better strategy. It should be noted that total volatile organic compounds (TVOC) is a concept still under development, there is no standard measurement method for TVOC, and numbers reported by different authors could vary widely due to different measurement protocols.

Figure 7 also shows the short-term variation in VOC source strengths over a period of four days, beginning at 6 am on Friday before the building was occupied, carrying over the weekend when only a few occupants were in the building, and continuing until 6 pm on Monday. It is clear from the data in *Figure 7* that the source strengths were greatest during the occupied day, low in the evenings even when the HVAC system was off, and low on the weekends when few people were in the building. Therefore, the source of VOCs was activity-related.

Closer comparison of chromatographs of building samples and those of the liquids used by the copiers in the building confirmed that the copiers were the major source of VOCs.

NIST investigators also conducted a questionaire survey of the occupants after their move into the building.[7] The survey's purpose was to determine the effects of office design features on job performance and satisfaction. About 20% of the respondents rated "air quality" in the building as poor. Almost 30% were disturbed by

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air "stuffiness." Odors did not seem to be a problem. The most frequent health-related worker complaint was difficulty in concentration. Complaints of eye irritation, headaches and sleepiness were also higher than estimated neutral responses.

Summary

This investigation was designed to establish a long-term record of a modern office building's thermal and environmental performance and to document what parameters in the design, construction and operation will affect this performance. Other than initial problems associated with "debugging" the HVAC system and controls, the building has adequate ventilation under most operating conditions.

The building envelope is not tight for a new structure and infiltration is a significant source of building air exchange. The levels of CO_2, formaldehyde, radon and respirable particles are well within the established guidelines.

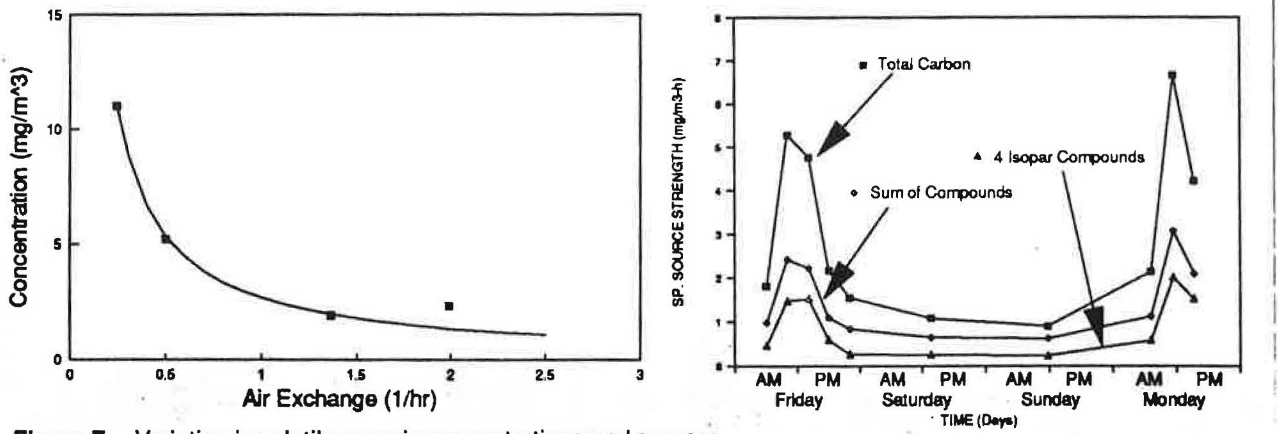

Figure 7. Variation in volatile organic concentrations and sources.

Table 1. Long-Term Variations in the Concentrations and Specific Source Strengths of Individual VOC

	Concentration (µg/m³)				Specific Source Strength (µg/m³-h)			
Date	8/4/87	10/14/87	1/13/88	10/28/88	8/4/87	10/14/87	1/13/88	10/28/88
Time	20:00	17–19:00	15–17:00	15–17:00	20:00	17–19:00	15–17:00	15–17:00
Vent. Rate	0.5	1.36	0.24	1.99	0.5	1.36	0.24	1.99
Compound								
Oxygenated								
2-Propanol	14.8	20.2	137.2	26.5	5.8	21.9	31.6	52.6
2-Propanone	50.1	28.8	66.6	32.4	22.1	27.0	14.9	49.7
2-Butanone	40.9	6.2	15.3	5.7	19.0	2.5	2.0	7.6
Chlorinated								
Dichloromethane	32.4	2.6	13.4	2.7	15.9	1.3	2.7	5.4
1,1,1-Trichloroethane	13.5	13.8	119.7	17.1	5.4	13.6	27.5	27.0
Trichloroethane	16.4	7.2	58.2	14.8	8.2	9.7	11.0	27.6
Alkane + Cycloalkane								
2-Methylbutane	31.9	53.8	81.6	26.2	13.1	31.7	16.1	44.7
n-Hexane	11.3	10.0	24.0	9.2	5.7	6.7	3.7	14.6
Cyclohexane	5.7			2.7	2.4			4.2
n-Heptane	4.8	3.1	12.6	3.6	2.0	2.7	0.2	5.5
3-Methylhexane	6.0	4.0	14.7	3.5	2.4	3.1	0.0	5.2
Methylcyclohexane	5.1			1.7	2.4			2.5
2,2,4-Trimethylpentane	2.4	1.8	8.0	3.0	1.0	1.3	0.7	6.0
1,4-Dimethylcyclohexane	3.1				1.6			
n-Nonane	39.6	10.6	149.1	33.9	19.7	11.4	35.3	63.0
2,2,5-Trimethylhexane	2.4				1.2			
Isopar 2	147.0	82.5	638.7	95.4	72.8	104.2	151.7	179.7
n-Undecane	115.6	57.3	831.3	48.3	55.2	71.3	196.8	85.7
n-Dodecane	49.1	10.6	280.8	10.9	21.8	5.9	67.0	17.6
n-Tridecane		6.0	111.9	8.5		5.8	26.2	13.8
n-Tetradecane		36.1	245.3	27.0		43.0	57.9	49.5
Aromatic								
Toluene	60.4	81.3	91.0	33.1	22.7	80.9	13.7	50.2
Ethylbenzene	11.8	7.0	18.7	7.5	5.3	4.9	2.3	11.4
1,2-Dimethylbenzene	17.2	8.7	25.8	8.1	7.6	5.8	4.1	12.0
1,3-, 1,4-Dimethylbenzene		18.1	54.5	18.3		11.7	8.8	26.6
1,3,5-Trimethylbenzene	4.1				1.6			
Totals								
Sum of individual VOC	685	470	2,998	440	315	466	674	762
Total organic carbon	5,200	1,900	11,000	2,300	2,500	2,400	2,500	4,300

One area of concern is the airflow from the garage into the occupied space. This airflow can cause high CO levels in the vicinity of elevator shafts and stairwells on the upper levels and near the loading dock. The garage exhaust fans are adequate to reverse this flow but, in the automatic mode, they currently do not operate long enough to do so. A change in their controls, or an attempt to isolate the vertical shafts (stairs and elevators) from the garage, would alleviate these problems.

There is no evidence of any significant outgassing of pollutants from the building's materials and furnishings. However, there are at least 37 VOCs in the interior air that seem to be related to the activities occurring inside the building. The levels of all these compounds are at least two orders of magnitude below established limits (1/10 of the permissible exposure limits). However, the vast amount of VOCs found in the building are compounds for which no extensive research has been done to establish irritant levels. Therefore, these compounds could be a source of complaints from the building's occupants at low ventilation rates. ■

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