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Effect of Ventilation Rate in a Healthy Building

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ABSTRACT

A study was conducted in a 20-story government office building to quantitatively assess the effect of ventilation rate on measured and perceived indoor air quality (IAQ) and comfort. The building has not experienced occupant complaints and, therefore, is thought to be healthy. IAQ/comfort monitoring was conducted and occupant surveys were administered during two separate weeks—one with the building at a ventilation rate near 20 cfm/person and the other near 35 cfm/person—within both the summer and winter seasons. Monitored pollutant levels at either ventilation rate were well within existing guidelines or standards. The IAQ parameter most affected by ventilation was CO_2, for which concentrations were lower at the higher ventilation rate. For most other IAQ parameters, monitored levels were either uniformly low or highly variable. Measured comfort parameters were similar for the two ventilation rates, and occupant perceptions of IAQ and comfort were largely unaffected by the ventilation rate. Despite these limited differences in measured and perceived IAQ/comfort, occupants consistently reported fewer health symptoms in the presence of higher ventilation.

INTRODUCTION

Indoor air quality (IAQ) and possible associated health problems have become major concerns for occupants of commercial buildings. The air quality in a building can be affected by factors such as indoor pollutant sources (e.g., furnishings, machinery, and the occupants themselves), outdoor sources, air exchange rates, and air-cleaning devices. In cases where IAQ problems attributable to indoor sources are detected, the changes to furnishings, cleaning devices, or occupant activity patterns needed to improve the situation could be difficult to implement. In such situations, the rate of air exchange is one factor that can be altered more readily, such as by changing damper settings for intake of outdoor air.

An impetus for increased ventilation is provided by guidelines or standards such as *ASHRAE Standard 62-1989* (ASHRAE 1989), which specifies indoor levels considered to be acceptable for pollutants such as carbon monoxide (CO), total suspended particles, carbon dioxide (CO_2), and ozone. Further, the standard indicates ventilation rates for specific types of occupied spaces (e.g., 20 cfm/person for office spaces) expected to achieve acceptable levels of IAQ by reasonably controlling the levels of contaminants common to these spaces, assuming that prevailing outdoor levels of such contaminants are acceptable.

To date, limited quantitative data have been collected to relate increased outdoor-air intake to commonly measured IAQ or comfort parameters. The purpose of this study (NYSERDA 1990) was to quantitatively assess the effect of ventilation rate on (1) indoor air quality and associated parameters in an occupied office building and (2) occupant perceptions of air quality and comfort in the building. The study was performed in a 20-story government office building in Albany, New York, that has not experienced occupant complaints and, therefore, is thought to be a healthy building.

STUDY DESIGN AND MONITORING METHODS

A preliminary evaluation of the heating, ventilating, and air-conditioning (HVAC) system indicated that approximately 30 to 35 cfm/person of outdoor air was provided at existing damper settings, based on a nominal building occupancy of 600 persons. The HVAC system includes two air-handling units that serve the perimeter of the building through induction supply-air units and two other units that serve the core area of the building through ceiling diffusers. The perimeter system has separate zones that serve the north and south sides of the building, and the core system is zoned to serve the upper and lower halves of the building.

To properly assess differences in IAQ between high and low ventilation rates within the building, a monitoring schedule of four weeks was devised. The HVAC systems were initially set so that the approximate amount of outdoor air per person would be equal to 20 cfm. After the system was allowed to run at that setting for a week, the first week of monitoring was performed. The HVAC systems were then adjusted to a nominal 35 cfm of outdoor air per person. The system was again allowed to run for a week before the second week of monitoring was performed. The initial HVAC evaluation and the first two weeks of monitoring were completed in the summer of 1989. An identical two weeks of monitoring was performed in January 1990.

A stratified random sampling strategy was developed for selection of 10 primary and 15 secondary monitoring sites. As shown later, the primary sites were monitored more intensely than the secondary sites. The building was stratified into upper

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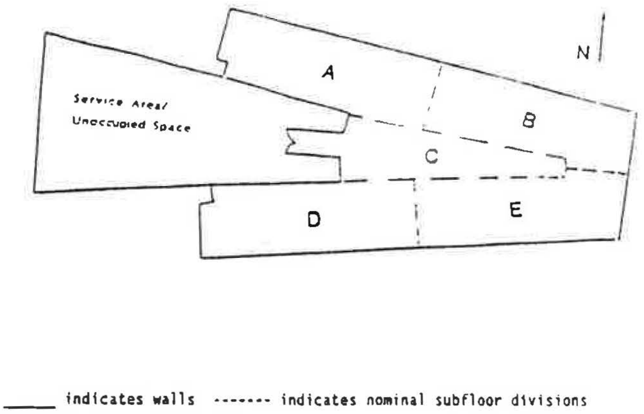

Figure 1 Building floor plan indicating subdivision for selection of monitoring sites

and lower halves served separately by the two core HVAC systems. Within each stratum, floors were selected at random with probabilities proportional to the number of occupants on each. Sampling was performed with replacement so that any floor could be selected more than once. Each of the 18 occupied floors in the building was divided into five subfloor areas (A, B, C, D, or E in Figure 1). Subfloor areas were selected at random for each chosen floor, subject to the constraint that each subfloor area be represented at least once within the 10 primary areas and once within the 15 secondary areas. A representative monitoring site was then chosen judgmentally for each chosen subfloor area, with consideration given to maintaining proximity to most work stations while avoiding direct impacts of air diffusers, local heat sources, or occupant activities.

The monitoring strategy (Table 1) included real-time monitoring together with integrated and grab samples. Primary sites were monitored on Monday, Wednesday, and Friday each week, whereas secondary sites were monitored on Tuesday and Thursday. Both real-time monitoring and integrated sampling were performed at the primary sites, whereas secondary sites were restricted to real-time monitoring. Real-time monitoring was conducted using instrumentation mounted on a mobile cart that was parked at each monitoring site for about five minutes, once each morning and afternoon. The specific sequence for visiting monitoring sites was determined randomly.

In addition to real-time measurements of CO_2, CO, respirable particles (RSP), and comfort parameters with the mobile cart, eight-hour integrated samples for analysis of formaldehyde, nicotine, and RSP were collected at the 10 primary monitoring sites on Monday, Wednesday, and Friday. Due to higher costs, integrated sampling of volatile organic compounds (VOCs) was restricted to two primary sites in addition to samples from the HVAC return duct of the perimeter HVAC system; grab samples for microbial aerosols (bacteria and fungi) were also taken at these sites. Outdoor levels of most parameters were monitored in an intake duct for the HVAC system. Building-wide air exchange rates were determined through periodic injections of sulfur hexafluoride (SF_6) directly into the primary air supply ducts followed by sequential syringe samples collected in the HVAC return ducts of the four air-handling units over a period of several hours.

Building occupants were not aware of ventilation conditions when monitoring was conducted. A questionnaire was designed to assess occupant perceptions of temperature, humidity, air movement, stuffiness, thermal environment, odors, tobacco smoke, and dust during each week of monitoring. The questionnaire also asked occupants if they experienced any

TABLE 1
Monitoring Strategy for Air Quality, Comfort, and Air Exchange Parameters

	Number of Monitoring Sites			
Measurement Method/Parameters	Primary	Secondary	HVAC Return	Outdoors
Real-time Monitoring*				
Carbon Dioxide/Monoxide, Temperature, Humidity	10	15	--	1
Respirable Particles, Air Velocity	10	15	--	--
Integrated Sampling**				
Formaldehyde, Nicotine, Respirable Particles	10	--	--	--
Volatile Organic Compounds	2	--	1	1
Grab Samples				
Microbial Aerosols	2	--	1	1
Sulfur Hexafluoride (air exchange)	--	--	3	--

* A mobile cart was parked at each indoor site for about 5 minutes each morning and afternoon

** Nominal sampling duration of 8 hours (8:00 a.m. to 4:00 p.m.)

selected health symptoms (Figure 2) while at work and, if so, whether they believed the symptoms to be related to the building environment. The survey was administered each morning and afternoon on Monday, Wednesday, and Friday to approximately 60 occupants whose work stations were near a primary monitoring location. Participants were asked to not discuss their responses with one another, and technicians collected most questionnaires soon after they were administered to minimize opportunities for discussion that could lead to clustering of responses.

A pretest was performed in August 1989. This effort included both real-time monitoring with the mobile cart and collection of integrated samples at a subset of four of the ten primary locations. Radon concentrations were also measured during the pretest; samples were collected with charcoal canisters over a three-day period at three randomly selected locations on each of four floors. Questionnaires developed for the occupant survey were not pretested in the building under study to avoid the possibility of preconditioning the respondents. Instead, these survey instruments were tested for clarity, logic, and required times for completion using coworkers in an office building that was occupied by the survey team.

MONITORING RESULTS

Typical monitoring results for CO, formaldehyde, ozone, RSP, radon, and CO_2 in the building are shown in Table 2 in

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10.  Please indicate whether you have experienced any of the
     following symptoms while at work in this building this
     morning:

     a.  Headache......................... 1 [ ] No  2 [ ] Yes   [ ]
     b.  Nausea........................... 1 [ ] No  2 [ ] Yes   [ ]
     c.  Runny/stuffy nose................ 1 [ ] No  2 [ ] Yes   [ ]
     d.  Sneezing......................... 1 [ ] No  2 [ ] Yes   [ ]
     e.  Cough............................ 1 [ ] No  2 [ ] Yes   [ ]
     f.  Wheezing/whistling in chest...... 1 [ ] No  2 [ ] Yes   [ ]
     g.  Shortness of breath.............. 1 [ ] No  2 [ ] Yes   [ ]
     h.  Chest tightness.................. 1 [ ] No  2 [ ] Yes   [ ]
     i.  Dry/itching/tearing eyes......... 1 [ ] No  2 [ ] Yes   [ ]
     j.  Burning eyes..................... 1 [ ] No  2 [ ] Yes   [ ]
     k.  Problem with contact lenses...... 1 [ ] No  2 [ ] Yes   [ ]
     l.  Sore/dry throat.................. 1 [ ] No  2 [ ] Yes   [ ]
     m.  Sleepiness or drowsiness......... 1 [ ] No  2 [ ] Yes   [ ]
     n.  Chills or fever.................. 1 [ ] No  2 [ ] Yes   [ ]
     o.  Dizziness/lightheadedness........ 1 [ ] No  2 [ ] Yes   [ ]
     p.  Dry or itchy skin................ 1 [ ] No  2 [ ] Yes   [ ]

11.  If you checked "Yes" for any of the above symptoms and you
     believe that they may be related to the air quality or
     thermal environment in the building, then check the box to
     the right in the above question for the symptoms that apply.
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Figure 2 Questions concerning health symptoms while the building was monitored

relation to existing standards or guidelines. All measured concentrations were well within these benchmarks, consistent with the low frequency of occupant complaints in the building. The remainder of the results presented in this section focus on comparisons between the two ventilation settings that were studied.

The target ventilation rates (i.e., rates of outdoor air supplied to the building through mechanical ventilation systems) were 20 and 35 cfm/person, assuming an occupancy of 600 persons. The actual rates, based on volumetric airflows calculated from duct-size and air-velocity measurements (ASTM 1985), were 16.5 and 38.0 cfm/person for the two weeks of summer monitoring and 12.2 and 31.5 cfm/person for the two weeks of winter monitoring. Weekly average air exchange rates, based on tracer-dilution measurements (ASTM 1980) and reflecting a combination of air infiltration and mechanical ventilation, were 0.83 and 1.06 air changes per hour (ach) during summer monitoring and 0.83 and 1.34 ach during winter monitoring. Thus, although differences in mechanical ventilation rates were greater than twofold, the total air exchange for the two ventilation settings differed by less than a factor of two due to air-leakage contributions.

CO_2 concentrations were significantly lower ($p < 0.05$) at the higher ventilation rate during both summer and winter (Table 3), consistent with the increased air exchange. CO concentrations were also significantly lower under the high-ventilation setting, but the difference is of little practical significance because prevailing concentrations were consistently near the detection limits for the monitoring instrument. Respirable particles measured on a real-time basis with an optical sensor were somewhat higher during each season with increased ventilation, but the differences are not statistically significant. Winter RSP levels were substantially lower than those measured during summer, due primarily to the fact that several agencies occupying the lower half of the building initiated no-smoking policies between the two monitoring periods. Similarly, integrated RSP (gravimetric method) and nicotine levels were substantially lower in the winter (Table 4) but were not greatly impacted by ventilation. Formaldehyde levels were quite low and unaffected by ventilation rates, and ozone levels were uniformly below detection limits.

During the summer, monitored indoor VOCs (Table 5) were substantially higher for the higher ventilation rate, but outdoor levels were also much higher during the week with high ventilation. During winter monitoring, when outdoor VOC levels were slightly lower for the high-ventilation week, indoor levels were also somewhat lower. The monitored levels of bacteria and fungi (Tables 6 and 7) generally were very low, an order of magnitude

TABLE 2
Summary of Measured Concentrations for Selected Pollutants in Relation to Existing Standards or Guidelines

Pollutant	Standard or Guideline	Typical Result for Study Building
Carbon Monoxide	9 ppm (USEPA)	<2 ppm
Formaldehyde	100-400 ppb (various)	10 ppb
Ozone	0.12 ppm (USEPA)	Below detection limits
Suspended Particles	Average -- 75 $\mu g/m^3$ (USEPA) Maximum -- 260 $\mu g/m^3$	15 - 30 $\mu g/m^3$ (RSP)
Radon	4 pCi/L (USEPA)	<1 pCi/L
Carbon Dioxide*	1,000 ppm (ASHRAE)	600 ppm

*Indicator of adequacy of ventilation

TABLE 3
Real-Time IAQ Monitoring Results for Summer and Winter, by Ventilation Rate

Parameter	Average ± Standard Deviation	
	Low Ventilation	High Ventilation
Summer		
Carbon dioxide, ppm	550 ± 29*	526 ± 54
Carbon monoxide, ppm	1.1 ± 0.4*	0.7 ± 0.3
Respirable particles, μg/m³	54.5 ± 36.1	60.0 ± 86.6
Winter		
Carbon dioxide, ppm	637 ± 76*	569 ± 58
Carbon monoxide, ppm	1.5 ± 0.7*	0.5 ± 0.3
Respirable particles, μg/m³	20.6 ± 38.3	24.2 ± 45.3

*Significantly higher ($p < 0.05$)

TABLE 4
Integrated IAQ Monitoring Results for Summer and Winter, by Ventilation Rate

Parameter	Average ± Standard Deviation	
	Low Ventilation	High Ventilation
Summer		
Formaldehyde, ppb	8.1 ± 7.7	11.1 ± 4.4
Nicotine, μg/m³	0.73 ± 1.96	1.17 ± 2.53
Respirable particles, μg/m³	24.0 ± 19.5	31.5 ± 19.1
Winter		
Formaldehyde, ppb	11.1 ± 4.4	10.0 ± 3.3
Nicotine, μg/m³	0.14 ± 0.71	0.26 ± 1.05
Respirable particles, μg/m³	17.0 ± 12.0	24.3 ± 17.8*

*Significantly higher ($p < 0.05$)

TABLE 5
VOC Monitoring Results at Four Sites for Summer and Winter, by Ventilation Rate

Monitoring Site	Concentration, μg/m³	
	Low Ventilation	High Ventilation
Summer		
6D	200.9	233.5
18A	94.9	335.1
HVAC return	156.5	638.6
Outdoors	4.2	220.2
Winter		
6D	204.8	153.4
18A	175.0	173.8
HVAC return	203.9	194.7
Outdoors	79.2	64.6

TABLE 6
Mesophilic Bacteria Monitoring Results at Four Sites for Summer and Winter, by Ventilation Rate

Monitoring Site	Concentration, CFU/m³	
	Low Ventilation	High Ventilation
Summer		
6D	85.1	299.7
18A	88.8	48.1
HVAC return	55.5	44.4
Outdoors	388.5	107.3
Winter		
6D	25.7	66.3
18A	40.7	40.7
HVAC return	7.3	11.0
Outdoors	74.0	66.7

TABLE 7
Fungi Monitoring Results at Four Sites for Summer and Winter, by Ventilation Rate

Monitoring Site	Concentration, CFU/m³	
	Low Ventilation	High Ventilation
Summer		
6D	81.4	53.7
18A	133.2	22.2
HVAC return	117.3	13.9
Outdoors	555.1	488.4
Winter		
6D	5.5	27.5
18A	16.5	7.3
HVAC return	7.3	7.3
Outdoors	68.5	75.2

or more below levels that have been measured in residences (e.g., Tyndall et al. 1987) or are considered normal for residential/commercial buildings (ACGIH 1989). Bacteria levels (Table 6) were sometimes higher and sometimes lower during the high-ventilation week, depending on the specific monitoring site. Although the bacteria levels appear to be consistently highest for site 6D under high-ventilation conditions, such apparent differences may be misleading because of substantial day-to-day variations in the monitoring results. For example, for the high-ventilation week during summer, mesophilic bacteria for site 6D measured 821 cfu/m^3 on Monday vs. 33 and 44 cfu/m^3 on Wednesday and Friday, respectively. During the summer, fungi levels (Table 7) were lower at the higher ventilation rate, but outdoor levels were also lower during that week. During the winter, fungi levels were uniformly low indoors and much lower outdoors than during summer.

Comfort indicators—temperature and relative humidity—had no apparent relationship with ventilation rate. Indoor temperature averaged 75 °F during summer and 73 °F during winter, regardless of the ventilation rate, and relative humidity averaged near 50% during the summer and near 30% during winter. Despite these similarities, a larger percentage of occupants indicated that the thermal environment was unacceptable under high ventilation during the summer (Table 8), but the difference in acceptability between ventilation rates for summer is not statistically significant. During the winter, there was little difference in acceptability of the thermal environment for the two ventilation rates. Occupant perceptions of air-quality indicators—odors, tobacco smoke, and dust—generally were similar for the two ventilation conditions during both summer and winter. The percentage of occupants indicating that air quality was unacceptable with respect to tobacco smoke was significantly higher under high ventilation during winter, but the percentages were quite low for both ventilation settings.

Although both measured and perceived air quality/comfort were largely unaffected by the ventilation rate, respondents reported significantly fewer health symptoms when the ventilation rate was higher (Table 9). During both summer and winter, the percentage of respondents checking at least one symptom on the list was about a third lower with higher ventilation. The per-

TABLE 8
Occupant Perceptions of IAQ during Summer and Winter Monitoring, by Ventilation Rate

Parameter	Percent Indicating Unacceptable	
	Low Ventilation	High Ventilation
Summer		
Thermal environment	12.1	18.1
Odors	0.0	1.6
Tobacco smoke	0.9	3.5
Dust	25.9	25.9
Winter		
Thermal environment	20.6	19.6
Odors	1.6	2.6
Tobacco smoke	1.6	3.7*
Dust	20.3	17.7

*Significantly higher ($p < 0.05$)

TABLE 9
Health Symptoms Experienced by Occupants during Summer and Winter Monitoring, by Ventilation Rate

Parameter	Percent Experiencing One or More Symptom	
	Low Ventilation	High Ventilation
Summer		
All health symptoms	49.1*	33.6
Building-related symptoms	29.3*	19.8
Winter		
All health symptoms	42.9*	31.6
Building-related symptoms	23.5	20.9

*Significantly higher ($p < 0.05$)

cent of respondents who experienced one or more symptoms and thought that at least one of the symptoms was building-related (i.e., related to the air quality or thermal environment in the building) was also consistently lower with higher ventilation, but only the summer difference is statistically significant.

DISCUSSION AND CONCLUSIONS

The results collectively indicate that the building investigated under this study does not have any apparent major indoor air quality problems. For pollutants for which guidelines or standards exist, the monitored levels were well within those benchmarks. The monitored CO_2 levels indicate that adequate ventilation is being provided to building occupants. The low CO levels indicate that there was not any significant impact from traffic on adjacent roadways or parking areas during the four weeks of monitoring. The low formaldehyde levels indicate that significant new sources have not been introduced in the building. All summer, fungi levels were lower indoors than outdoors, suggesting that there are no significant sources in the building. This notion is reinforced by the even lower fungi levels indoors during winter when outdoor levels receded due to lack of outdoor sources. The systematically lower nicotine and RSP levels during the winter demonstrate the effectiveness of source control (i.e., enactment of no-smoking policies on selected floors between summer and winter monitoring).

Although the mechanical ventilation rate was increased by approximately a factor of two by experimental design, the resultant difference in the overall air exchange rate for the building was less than twofold due to sizable contributions from air infiltration. The monitored IAQ parameter that was most significantly impacted by increased ventilation was CO_2, for which concentrations were lower with higher air exchange. For most other IAQ parameters, monitored levels were either uniformly low or highly variable.

For RSP, nicotine, microbial aerosols, and VOCs, localized sources may play a more dominant role than the overall ventilation rate for a building. Measured comfort parameters were similar for the two ventilation rates, and occupant perceptions of indoor air quality and comfort were largely unaffected by the ventilation rate.

Despite the limited differences in monitored IAQ/comfort and occupant perception thereof, survey respondents consistently reported fewer health symptoms in the presence of higher ventilation rates. These differences might indicate potential health benefits from increased ventilation, especially if such a finding can be replicated. The differences may be due to relatively subtle environmental factors that cannot readily be discerned through monitoring or the five senses, but which nonetheless might have some impact on human health. For the building studied, a more comprehensive and longer-term occupant survey would be needed to verify or refute the current findings.

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REFERENCES

ACGIH. 1989. *Guidelines for the assessment of bioaerosols in the indoor environment.* Cincinnati: American Conference of Governmental Industrial Hygienists.

ASHRAE. 1989. *ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality.* Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASTM. 1980. *E741-80, Standard practice for measuring air leakage by the tracer dilution method.* Philadelphia: American Society for Testing and Materials.

ASTM. 1985. *D3464-75, Standard test method for average velocity in a duct using a thermal anemometer.* Philadelphia: American Society for Testing and Materials.

NYSERDA. 1990. *Impact of ventilation rate on indoor air quality and comfort in agency building no. 2.* Report No. IE-2248, prepared for New York State Energy Research and Development Authority. Germantown, MD: GEOMET Technologies, Inc.

Tyndall, R.L., C.S. Dudney, A.R. Hawthorne, R. Jernigan, K. Ironside, and P. Metler. 1987. "Microflora of the typical home." *Proceedings of the 4th International Conference on Indoor Air Quality and Climate,* Vol. 1, pp. 617-621. West Berlin: Institute for Water, Soil and Air Hygiene.