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The Human Equation: Health and Comfort

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The Human Equation: Health and Comfort

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Pollutants/Health Effects

SICK BUILDING SYNDROME TRACED TO EXCESSIVE TOTAL SUSPENDED PARTICULATES (TSP)

Carl W. Armstrong **Peter C. Sherertz** **Gerald C. Llewellyn**

ABSTRACT

An epidemiological and environmental investigation into the air quality of a high-rise public office building was conducted in July 1988. A walkthrough inspection revealed particulate (dust) soiling of ceiling and work surfaces in occupied sections of the service floor. Building air samples obtained by high-volume air pumps and cassette filters revealed elevated concentrations of total suspended particulates (TSP) which ranged up to 1.07 mg/m³ (more than 17 times the Building Officials and Code Administrators [BOCA] standard). In 17 (59%) of the 29 areas tested, TSP levels exceeded the BOCA standard of < 0.06 mg/m³ (annual average). Recorded temperatures, relative humidity readings, and supply of outside air were within acceptable limits. Testing for volatile organic compounds, combustion products, formaldehyde, ozone, and fungal spores revealed no levels of concern. A survey of occupants in selected units was conducted with 94% participation. Fifty-five percent indicated that they had experienced symptoms that appeared or worsened during their working hours. Of these, 47% indicated that they had missed work because of their symptoms. Common symptoms were headache and sinus/upper respiratory congestion compatible with air contamination by TSP or other irritants. In multivariate analysis, illness was found to be significantly associated with air TSP concentration ($P < 0.002$), CO_2 concentration, average number of hours worked per week, gender, and smoking status. This is one of very few outbreaks of building-related illness where occupant illness has been associated with exposure to elevated levels of an environmental contaminant (TSP).

INTRODUCTION

Building-related illness episodes have been reported more frequently in recent years as buildings have been made more airtight to conserve energy (Hicks 1984). Modern high-rise office buildings are constructed primarily of steel, glass, and concrete, with large windows that cannot be opened. These buildings have become totally dependent on mechanical systems for air conditioning. The latter situation definitely allows for better central control and certain other advantages. However, this situation may also allow contaminants that have been introduced into the system to remain for extended periods. These contaminants may be present in make-up air or may be introduced from indoor activities, furnishings, building materials, surface coatings, and air-handling systems and/or their treatment components. Symptoms often reported are eye, nose, and throat irritation; headache; fatigue; and sinus congestion (Melius et al. 1984). In some cases, the cause of the symptoms has been ascribed to an airborne contaminant, such as formaldehyde, tobacco smoke, or insulation particles, but most commonly a single contaminant is not found to be responsible and outside air ventilation is often found to be inadequate.

Resources generally consulted that provide air quality criteria, guidelines, and/or recommendations include: National Institute for Occupational Safety and Health (NIOSH) criteria documents and recommendations for occupational exposures; the U.S. Department of Labor (OSHA) federal occupational health standards (CDC 1988); the indoor air quality standards developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE 1981a, b); and the standards in the model code of Building Officials and Code Administrators International, Inc. (BOCA 1983). The BOCA standards have been adopted by the Virginia General Assembly as the Uniform Statewide Building Code.

The first two sources provide permissible exposure limits (PEL) based on airborne concentrations of substances to which healthy adult workers may be occupationally exposed in the workplace environment for an 8- to 10-hour workday or a 40-hour workweek during a working lifetime without unreasonable risk (e.g., 1/10,000 chance of death). They also provide the concentration of a chemical which would be "immediately dangerous to life or health" (IDLH), defined as the maximum level from which one could escape within 30 minutes without any escape-impairing symptoms or any irreversible health effects. The ASHRAE standards are general air quality standards for indoor environments and are applicable for the general population exposed continuously for 24 hours a day without known toxic effects. For chemicals not covered in its standard, ASHRAE recommends using a limit that is 1/10 of OSHA's PEL.

Investigations of building-related discomfort and/or illness may incorporate evaluations of one or more factors. These include temperature, humidity, fresh air ventilation, TSP (dust), products of combustion, environmental tobacco smoke (ETS), formaldehyde, microorganisms and allergens, volatile organic compounds (VOC), ozone, and radon.

The investigated building was a high-rise state government office building housing more than 1200 employees. Completed in December 1980, it would be considered energy efficient by current construction standards. No asbestos insulation was used in construction. Shortly after occupancy, some of the windows were discovered to leak when it rained; they were subsequently sealed. The service floor was designed for storage of office materials and maintenance equipment and was not intended for occupancy by office personnel. However, some of the equipment (e.g., film library) used by one state agency was too heavy to be placed on the tower floors and was placed in an area of the service floor along with associated personnel.

The heating, ventilating, and air-conditioning (HVAC) system supplied air to the building tower via a variable-volume, multi-zone system. Air intakes were located near ground level approximately 50 ft from a major interstate highway and on the 13th floor. Filtration was provided by elec-

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rostatic filters (estimated efficiency of 10% to 20%). A spray unit was designed to aid in the evaporative cooling process during the spring and fall by applying water to the evaporator coils. Subsequently, this unit was believed to be defective in design when excess water, which should have collected in a drainage pan under the coils, was carried over the pan by air currents to the floor between the unit and the air ducts. This standing water promoted the growth of slime. Slime control was achieved through cleaning and use of biocides.

The perimeter of the tower is heated and cooled by two air-handling units (one for the northeastern and northwestern quadrants, and one for the southeastern and southwestern quadrants). Originally, these units were designed to be linked to sensors that detect solar heat gain on the building and automatically vary the air supply and temperature. Due to limitations in funding, this automatic system was never completed and manual adjustments are made by building engineers. Two air-handling units supply 55°F air to the interior of the building (one for the northeastern and northwestern quadrants, and one for the southeastern and southwestern quadrants). The temperature of this air is adjusted, via thermostats on each floor, by mixing with the necessary amount of warmer air. Separate air-handling units provide ventilation to the service floor, the second and third connector floors, the mezzanine, and the first floor (cafeteria). Air ducts terminate in double, slot-type registers mounted in the suspended ceiling. Air to the exterior perimeter is supplied via registers above the windows. Air is returned via ducts located in the plenum above the ceiling. It is a policy of the Virginia Department of General Services (VDGS) that the indoor temperature in state buildings be maintained at a maximum of 68°F during the heating season, and at a minimum of 78°F during the cooling season.

In January 1984, the Virginia Bureau of Occupational Health (then within the Virginia Department of Health) investigated the 24th and 25th floors of this building in response to air-quality complaints. The principal finding of that study was an average humidity level of approximately 22%.

METHODS AND MATERIALS

Site Inspection

A walkthrough inspection was carried out, and the ventilation system was reviewed in detail with the maintenance engineer assigned to this building.

Environmental Sampling

It was decided to focus most of the sampling on randomly chosen floors (hereinafter referred to as the "study floors"): 9, 10, 14, 15, 16, 24, and the service floor (both floor 24 and the service floor were identified as "worst-case" floors). Additional, less extensive sampling was performed on other floors in the tower, as described below. Samples were collected on different days, depending on the type of test, during the period June 30 through July 19, 1988.

Infrared wavelength scans in the range between 2.5 m and 14.5 μm were performed on air samples taken in the office area of the service floor and in each quadrant (northern, southern, eastern, and western) of the tower study floors (as well as the 17th floor) using a portable, single-beam, infrared spectrophotometer (limit of detection equal to 1% to 5% of PEL values). Conventional, half-shift sampling methods were employed on study floors for TSP using high-flow pumps (calibrated at 10 L/min), and pre-weighed cassette filters. After sampling, the filters were desiccated overnight and reweighed to determine TSP. Carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde, sulfur dioxide (SO_2), and ozone were sampled with multigas detector pumps utilizing colorimetric tubes (detection limits were 5 ppm, 50 ppm, 0.1 ppm, 0.25 ppm, and 0.025 ppm, respectively). Carbon dioxide was measured at least once on each floor and twice (morning and afternoon) on the study floors. Carbon monoxide, nitric oxide, and formaldehyde were measured on the study floors and floor 17. Ozone was measured on floors 14 and 15; SO_2 was measured on these floors, as well as on 16, 17, 19, and 24. A sling psychrometer was utilized to determine the temperature and relative humidity on each floor.

Duplicate, 10-minute fungal spore counts were obtained on each study floor and outside (for comparison) using a particle-fractionating viable sampler with a calibrated air intake of 1 ft^3/min. Sabouraud's agar with chloramphenicol was used to culture fungi. Colonies were enumerated after a 48-hour incubation period at room temperature.

Epidemiology

A questionnaire was distributed to a majority of study-floor personnel on July 5, 1988. Requested information included job description, temperature/humidity and odor perceptions, presence and temporal characteristics of any work-associated symptoms, smoking status, and allergic history.

Data Analysis

Questionnaire and environmental data were analyzed separately using microcomputer software, then merged using floor quadrant as the linking variable. Statistical comparisons were performed utilizing the appropriate chi-square test, Fisher's exact test, or unpaired t-test. Statistical significance was defined as $P < 0.05$. Multivariate analysis (a stepwise, conditional, logistic regression model) was performed using microcomputer statistical software. The following independent variables were eligible for inclusion in the model: CO_2 concentration, temperature, relative humidity, TSP concentration, average hours worked per week, employee classification, gender, and current smoking status. Floor location was considered a surrogate for other, more relevant, risk factors, and it was not eligible for inclusion. The criterion for entry was $P < 0.1$.

RESULTS

Observations

On several floors, water stains were noted on some of the ceiling panels near windows, consistent with previous window leaks. Most floors were covered with carpet and furnished with movable, cloth-backed partitions. Remodeling construction and dust associated with such activity were noted on the tenth floor. Dark particulate soiling around the air registers was noted in the occupied section of the service floor. In addition, desks and other surfaces on the service floor were covered with fine, sootlike particulate matter. Evidence of high humidity also was noted on the service floor (e.g., carpet buckling and rusting of film canisters).

The HVAC inspection revealed little, if any, standing water in the condensate trays. Evidence was seen of leakage from a spray unit onto the floor adjacent to the unit, although no visible slime was present. Pre-filters were curling at the edges, apparently allowing a sizable amount of air to escape filtration. Outside air louvers were open, allowing outside air to constitute an estimated 20% of total airflow within the building.

Environmental Sampling

Volatile organic compounds (VOC), products of combustion (CO, nitrous oxide [NO], and SO_2), formaldehyde, and ozone were not detected on any of the study floors.

Air sample CO_2 concentrations ranged from 300 ppm (an outdoor control sample) to 850 ppm on floors 19 and 24 (the lowest indoor value was 400 ppm). The mean concentration for the study floors was 693 ± 91 ppm. As expected, the highest readings were obtained late in the afternoon and the lowest readings early in the morning.

Temperature readings ranged from 69°F (floor 17) to 76°F (floor 10) and relative humidity readings ranged from 25% (floor 14) to 51% (floor 5). For the study floors, the mean temperature was 73.7° ± 1.3°F. Twice a day during the period June 23 through July 9, 1988, temperature and relative humidity readings were made in each quadrant of several floors. The only extreme temperatures recorded were readings of 67°F on the morning of June 27 on floors 10 and 14 (the outside air temperature that morning was 56°F).

Viable fungal spore counts (average of duplicate measurements) were ≤ 18 colony-forming units (CFU)/m^3 on all study floors. This compared with outdoor counts of 85 CFU/m^3 on the tower rooftop, and 106 CFU/m^3 on the building patio.

The TSP concentrations ranged from negligible (southern quadrant of floor 16) to 1.070 mg/m^3 (service floor offices). The mean TSP concentration for the study floors (four quadrants per tower floor) was 0.128 ± 0.256 mg/m^3. Of the 29 areas tested, and assuming these results reflect 24-hour averages, only 12 (41%) had TSP concentrations within the building code standard (≤ 0.060 mg/m^3). Two areas (service floor and the western quadrant of floor 10) had TSP measurements above 1.0 mg/m^3 (more than 17 times the building code specification). Construction activity on the tenth floor was probably responsible for the high reading there.

Epidemiology

Completed questionnaires were returned by 94% (218/233) of personnel on the study floors. Only 28% of respondents felt that the temperature of their work location usually was satisfactory. Eight percent felt the environment was usually too hot, 24% felt it was too cold, and 39% felt it was usually too hot or too cold. Thirty-seven percent felt the humidity in the work location was satisfactory. Seven percent felt the humidity was usually too high, 36% thought it was too dry, and 15% judged it too high or too low. Sixty-four percent of the respondents had noted a foul odor coming from the ventilation system; the vast majority described it as a "dead fish" or "wet dog" smell, last noted in late May or early June 1988.

Fifty-five percent of the respondents indicated that they experienced symptoms that appeared or worsened during their working hours. The frequency of selected symptoms is shown in Table 1. Of these symptomatic respondents, 61 (51%) indicated that they had seen a physician because of their illnesses. Fifty-six (47%) indicated that they had missed work at some time because of these symptoms, and 15% noted that they had missed one to three days of work during the preceding 30 days. Although their symptoms appeared or worsened while at work, most symptomatic respondents indicated that there was no apparent connection between their symptoms and any particular season of the year, day of the week, or time of day. Dates of onset of illness, provided by 87 of the 120 symptomatic respondents, showed no temporal clustering of onsets other than at the time the building was first occupied (many who moved in after the building first opened noted that their onset dates were the same as the dates that they moved in).

The proportion of persons on each study floor reporting uncomfortable temperature and/or humidity, foul odor, or symptoms is shown in Table 2. The variation in the proportion of persons noting temperature- or humidity-related discomfort on study floors was significantly different from variation that one might expect due to chance alone ($P < 0.0001$). Illness rates also varied significantly by floor ($P < 0.02$). The proportion of persons noting a foul odor did not vary significantly by floor.

Preliminary univariate analysis suggested no association between illness and any of the environmental results (i.e., concentrations of CO_2, NO, formaldehyde, CO, viable fungal counts, TSP, temperature, or relative humidity). Univariate analysis indicated that illness was significantly associated with respondent employment classification. Personnel were grouped into three categories based on apparent level of responsibility: clerical, intermediate, and managerial. Although the range of attack rates for these three groups was not large (from a low of 47% for managers to a high of 67% for clerical staff), there was a significant inverse relationship between these ascending categories and illness rates ($P < 0.02$ by chi-square for trend). Illness was significantly associated with the average number of hours worked per week, ranging from 38% for those working less than 40 hours per week to 55% for those working more than 40 hours ($P < 0.005$ by chi-square for trend). Other questionnaire variables found to be significantly associated with illness were female gender (relative risk [RR] = 1.53, 95% confidence interval [CI] = 1.18–1.99, $P < 0.003$), and nonsmoking status (RR = 2.28, 95% CI = 1.39–3.76, $P < 0.003$). The following questionnaire variables were not found to be significantly associated with illness: agency where employed, length of time employed at current location, age of respondent, or history of allergies or of treatment for a lung condition.

For multivariate analysis, a computer model was constructed which was significantly predictive of illness ($P < 10^{-6}$). Through a stepwise process of forward selection and backward elimination of variables to achieve the best predictive capability, the computer model selected the following risk factors for inclusion: female gender ($P < 0.002$), nonsmoking status ($P < 0.002$), floor TSP concentration ($P < 0.002$), respondent's average number of hours worked per week ($P < 0.02$), and floor CO_2 concentration ($P < 0.09$). The following variables did not improve the model and were rejected: temperature, humidity, and respondent employment classification.

DISCUSSION

This investigation documented that a sizable fraction of the personnel surveyed have experienced symptoms primarily consisting of headache; eye, nose, and throat irritation; drowsiness; and difficulty concentrating. The situation is consistent with indoor air pollution or "tight building syndrome," which is now commonly recognized in many modern, climate-controlled, sealed buildings. In most instances, no specific chemical contaminants can be identified as the source of the problem, but inadequate ventilation with fresh outside air can frequently be demonstrated to contribute to the problem (Whorton et al. 1987).

In general, the symptoms identified here were experienced by a large proportion of the staff for varying lengths

TABLE 1

Frequency of Selected Symptoms Reported by High-Rise Office Building Personnel

mptom	Frequency
adache	61%
nus congestion	59%
sal irritation	58%
roat irritation	58%
owsiness	53%
e irritation	52%
ugh	37%
fficulty concentrating	26%
scle aches	19%
ills	16%
zziness	15%
ortness of breath	13%
eakness	9%
omach ache	8%
arrhea	8%
ver	7%
sh	5%
intness	4%

time while at work and disappeared within a period of urs after persons left the building. These features are content with an irritative rather than infectious or allergic process. Consistent with this was the finding of elevated TSP ncentrations on many of the study floors. Also, based on ultivariate analysis, TSP concentrations were found to be statistically significant predictor of illness. Although eleted TSP levels were found on a number of floors, the TSP oblem was most severe in the service floor office space, sed on observation and measurement. Apparently, soot m vehicular traffic on the adjacent interstate highway was ing drawn into the ventilation system, escaped adequate tration, and was dispersed indoors, especially on the service or.

Epidemiological studies linking health effects to TSP exsure have been conducted primarily in outdoor environents. In those studies, it has been difficult to accurately sess the independent contribution of TSP to health effects, ven that polluted air usually contains multiple contaminnts. In one study of 10,106 pre-adolescent children, the equency of cough, bronchitis, and transient lower respiratory illness was significantly associated with increased TSP vels in the outdoor air (Ware et al. 1986). The lowest annual erage TSP concentration at which temporary health effects re observable in sensitive groups (children and persons th underlying lung or heart disease) was about 0.24 mg/m^3, d the lowest 24-hour TSP concentration at which health fects were seen in bronchitic patients was about 0.35 mg/ (Holland et al. 1979).

Three host factors were found to be associated with illss. Several explanations could be offered for why the avage number of hours worked per week was found to be one ch risk factor. The most obvious is that if TSP in the air re responsible, at least in part, for many of the symptoms, en one would expect to see a "dose-response" effect where creasing exposures led to increasing probabilities of illness. cond, persons who indicated that they worked more than hours per week were more likely to enter the building on ekends. This is a time when the ventilation system was rtially shut down to conserve energy, and prevented the lution of other contaminants that might have contributed illness. Finally, ill respondents who had worked less than hours per week may have been less inclined to mention mptoms because of temporary job status and fear of dissal.

TABLE 2

Prevalence of Complaints by Floor in a High-Rise Office Building

Floor	Too Hot/Cold	Too Humid/Dry	Odor	Symptoms
09	82%	79%	82%	76%
10	69%	69%	63%	31%
14	67%	48%	67%	38%
15	87%	50%	44%	38%
16	85%	60%	70%	60%
19	59%	43%	63%	50%
24	71%	74%	52%	55%
Service	71%	79%	71%	75%

Nonsmoking status also was identified as a host risk factor. The reason for this is not clear. One possibility is that some smokers with a history of bronchitis may have attributed any exacerbation of smoking-related symptoms to their habit instead of to the building environment. In addition, given the inherent biologic variation within the human population, one would not expect all individuals to be equally susceptible to the irritative effects of TSP pollution. It is reasonable to speculate that the more sensitive individuals among the respondents would have experienced TSP-related symptoms earlier in their lives. These more sensitive individuals may have been less likely to be smokers than less sensitive individuals.

It is doubtful that there is any biologic reason for the higher illness rates among women (64% vs. 42% in men). The same finding has been noted in some other surveys and outbreak investigations of illnesses where gender differences were not anticipated (Henderson and Shelokov 1959). Given that complaints of symptoms may be interpreted by peers as a sign of weakness, and given strong cultural influences to avoid any appearance of weakness (especially among men), it is reasonable to speculate that such gender differences might be a result of greater reluctance among men to admit to having symptoms.

Although a number of the survey respondents complained of temperature- and humidity-related discomfort, our measurements showed very few deviations from the ranges recommended by ASHRAE or specified by the building code. A major limitation of our study is that it represents only a "snapshot" of conditions within the building. Since humidity control is not part of the HVAC system in this building (or any other state office buildings) and outdoor humidity levels are lower in the winter, it is very likely that indoor humidity levels would be much lower during the heating season. This was found to be true in the study of the 24th and 25th floors of this building in 1984. In that study, the average relative humidity level was found to be approximately 22%. At this level, it would be difficult, if not impossible, to manipulate temperature (even if energy conservation restrictions were not in place) in order to achieve a combination of temperature and relative humidity within the comfort zone suggested by ASHRAE.

Many survey respondents also had noted transient foul odors coming from the ventilation system. Most had last noted the smell in late May, which coincides with the time when the HVAC system spray unit was taken out of operation for the summer. It is likely that the smell observed by these occupants was generated by microorganism growth as a result of the believed design defect in this unit. Our sampling for fungal spores found no increased indoor concentration over outdoor levels, although our testing occurred after the spray unit had been dismantled and cleaned for the season.

RECOMMENDATIONS

Several recommendations were suggested to help remedy the situation in this office building. Better air filtration was needed to reduce indoor TSP concentrations to a level that complies with building codes, and which would not cause any adverse health effects. Better housekeeping, at least as a temporary measure until better filtration was in place, was suggested to help reduce TSP levels (especially important in areas where remodeling construction was taking place). At a minimum, it was suggested that a thorough dusting of surfaces and vacuuming of the movable partitions (in addition to routine cleaning) should be carried out on a semiannual basis. An examination of the cost-benefit ratio of adhering to ASHRAE comfort guidelines should be conducted. This would require a reexamination of the policy of not controlling humidity in state office buildings. If the spray unit was to continue to be used, an augmented maintenance program should be instituted to control microbial growth; ASHRAE considers the prophylactic use of disinfectants in the HVAC system, excluding cooling towers, to be unacceptable in most instances (ASHRAE 1987). After administrative review, the findings of this study and any plans for follow-up action should be shared with each agency in order to better inform concerned occupants in the building.

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DISCUSSION

David Mudarri, U.S. Environmental Protection Agency, Washington, DC: How do you suspect the TSP levels were related to smoking in the building or the use of ultrasonic humidifiers or to fungal spores, particularly in the basement? Each of these could be major sources of TSP.

P.C. Sherertz, Virginia Department of Health, Richmond, VA: Under the time constraints of this project, we were not able to consider much other than the TSP levels. We recognize many of the conditions you mentioned may have been directly related to our observed TSP levels.

Behzad Samimi, Graduate School of Public Health, San Diego State University, San Diego, CA: The use of the MIRAN gas analyzer is inappropriate for low concentrations of volatile organics. This instrument is only appropriate when known organic volatiles with relatively high concentrations are suspected to be present, which makes this instrument suitable for use primarily in occupational environments (where employees are working with solvents, etc.) and not in an office building situation.

You stressed in your study that TSP is the major factor in causing symptoms among employees. Did you conduct any analyses, i.e., scanning electron microscopy, elemental analysis or size distribution analysis, to determine the nature and sources of these particulate matter?

Sherertz: No.

Samimi: Did you take any air samples for incoming air (dampers) to see whether any particulates are present in incoming air?

Sherertz: No.

Carl Lawson, LRW Engineers Inc., Tampa, FL: Did you find humidity more heavily concentrated at lower floors? Did you test the computer room or not? What was the mildew content in this project?

Sherertz: No (to the first two questions). There were no gross fungi infestations noted during this study—only the smell which was reported by some personnel.

Charles J. Weschler, Bell Communications Research, Red Bank, NJ: The motors used in high-volume samplers can, themselves, generate particles. Were any precautions taken to prevent re-entrainment of these particles during the sampling for TSP?

Sherertz: No.

;YMPTOMS AND THE MICRO-ENVIRONMENT IN THE ;ICK BUILDING SYNDROME: A PILOT STUDY

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BSTRACT

In a cross-sectional investigation in one building, mplaints associated with the "sick building syndrome" ere measured on a linear analog scale questionnaire. t the same time, the micro-environment (environmental aracteristics in the breathing zone rather than area mples) was characterized by measuring temperature, lative humidity, respirable suspended particulates, car- n dioxide, noise level, lighting intensity, relative hu- idity, and airflow. No relationship was seen between e degree of symptoms and age, education, or duration employment at the building or time spent in the build- g on a daily basis. Statistically, complaints were gnificantly more frequent among smoking men. Envi- nmental characteristics associated with the increased mplaint levels in this group included decreased airflow locity and increased levels of respirable suspended par- ulates and dry-bulb temperature. In regression odels, there was an association between respirable sus- nded particulates and the levels of both mucous mem- ane and systemic complaints. Satisfaction with the ermal environment as predicted by perception of draft d not clearly contribute to the degree of symptoms, hough regression models did suggest that complaints ere not independent of thermal parameters. Lighting tensity was also associated with complaints. Future udies of the sick building syndrome should examine ultiple exposures simultaneously and include psycho- cial measures to identify predictors of complaints in door spaces.

NTRODUCTION

Complaints termed the "sick building syndrome" have d to numerous investigations in the last 15 years. They are ought to occur primarily in newly constructed office build- gs and, at least in the past, were thought to be due to adequate ventilation (Melius et al. 1984). Nevertheless, a de variety of causes have been identified in specific settings, cluding inadequate temperature and relative humidity con- ol, noise, lighting, vibration, volatile organic compounds d formaldehyde, microorganisms, environmental tobacco noke, pesticides, dust, entrainment of vehicle exhaust or ent and contaminated air and boiler fumes, fibers released m duct linings, and office machine offgases and odors reiss and Hodgson 1984; Hodgson and Kreiss 1986).

A group of investigators from Great Britain (Finnegan al. 1984) suggested that these complaints were related pri- arily to mechanical ventilation. The same group of authors obertson et al. 1985) was unable to identify differences in t-bulb globe temperature, dry-bulb temperature (temper- ure), relative humidity, air velocity, formaldehyde, or pos- ve or negative ions between several rooms in a building th natural and a building with mechanical ventilation, ie: both sets of rooms had high levels of complaints. Burge et al. (1987) investigated the frequency of complaints in 43 office buildings built over the last 50 years with a validated questionnaire. The symptoms were more common in buildings where the ventilation system also provided cooling and humidification, irrespective of the age of the buildings. A direct relationship between the level of complaints and air quality parameters was not described. Skov et al. (1987) examined indoor air quality symptoms in 14 modern Danish town halls and 14 older control buildings. The level of symptoms was related to a "fleecing" factor (carpets, upholstery, and horizontal surfaces) and the "macro-molecular component" of dust. They also demonstrated a relationship between the number of hours spent photocopying and using carbonless copy paper and the level of complaints. Other studies have demonstrated that ergonomic aspects (Stellman et al. 1985) and psychodynamic factors (Rowland et al. 1984) contribute to indoor air quality complaints.

Several studies have attempted to identify the actual cause of complaints in the sick building syndrome by measuring symptoms and environmental exposures. Robertson et al. (1985) were unable to demonstrate any measurable differences in the concentrations of environmental pollutants between rooms in a mechanically and a naturally ventilated building. They studied the rooms with the highest complaint rates and used area samples. Skov et al. (1987) did demonstrate a relationship between symptoms and both area samples measuring dust and a "macro-molecular" fraction, again in area samples.

Area samples in buildings may not be representative of the exposures in different points in single rooms. Physical characteristics such as windows and partitions, computers, and shelving may influence air currents. Radiant heat may lead to uneven distribution of pollutants. Finally, most pollutants result from point sources, so they will be diluted as a subject is farther removed from the source. The micro-environment around desks and within cubicles may have very different exposure characteristics than the macro-environment of a building. In addition, all applied occupational and environmental health research that attempts to relate dose to health effects suffers from the problem that dose is generally measured at several points in time and then extrapolated to allow development of exposure classifications over decades while most health effects are measured as a single result of these chronic exposures. Where the variability of sampling results is greater than the difference in average samples, and where the level of symptoms may change not merely from day to day but from hour to hour, such a strategy must fail.

No investigations in the peer-reviewed literature have attempted to characterize air-quality parameters in the micro-environment and set these characteristics in relation to the level of individual complaints at a given point in time. This report presents results of a cross-sectional investigation of a problem building using a self-administered, linear analog, self-assessment questionnaire to record short-term symptom

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levels at a given point in time and measures of the indoor air quality in the breathing zone during the completion of the questionnaire in an attempt to use a method to identify the pollutants leading to complaints.

METHODS

Background

The building was occupied in early 1984 and serves as an academic computing center, with offices and conference rooms for faculty and a large computer terminal hall for students. It is a three-story, "hermetically sealed" building with six ventilation zones through the floors, encompassing approximately 40,000 ft² of floor space. The basement (lowest floor) contains storage rooms, mechanical system rooms, and a computer repair shop. The ventilation is provided by variable-air-volume systems in each zone. The maintenance shop on the ground floor has its own ventilation system.

Complaints had begun almost immediately after occupancy and persisted for almost two years by the beginning of this survey. Multiple prior industrial hygiene surveys had failed to provide evidence of concentrations of formaldehyde and other volatile organic compounds in levels that, by themselves, could be expected to cause complaints in a high proportion of occupants. Formaldehyde area samples were in the range of 0.01 to 0.07 parts per million (ppm); carbon monoxide, 3 to 6 ppm; carbon dioxide, 540 to 780 ppm; and relative humidity, 44% to 58%; and part-per-billion (ppb) levels of 1,1,1-trichlorethane and other halogenated hydrocarbons, including freons used in computer maintenance, were found.

Design and Conduct of the Study

The authors designed a cross-sectional study to identify the level of short-term complaints and simultaneously measure indoor air quality characteristics. No attempt was made to measure ergonomic characteristics of the work stations, although building occupants are frequent users of computer terminals. A four-week period was set for this study, and the necessary instruments were rented. The technicians obtained all measurements at each subject's desk in the breathing zone while the study subject was actually completing the questionnaire. All measurements were obtained only once. The time required for completing data collection at each work station was approximately 45 minutes. Completion of the questionnaire required approximately 10 minutes, so measurements were begun while the subject sat at his or her desk and frequently were completed only after the subject had responded to the questionnaire. To ensure blinding, the technicians did not review the questionnaires. Two technicians alternated in obtaining measurements. All measurements were obtained between the hours of 1 p.m. and 5 p.m. on weekdays.

Population

All full-time building occupants were eligible to participate, i.e., staff and faculty. Students were excluded.

Questionnaire

Linear analog questionnaires (Bond and Lader 1974) are well described, with validation studies published in the British psychological literature. This questionnaire was originally used in the investigation of formaldehyde-related complaints in day-care centers (Olsen and Dossing 1982). More recently, it was used to identify complaints (Hodgson et al. 1987) in a building outbreak thought due to inadequate ventilation but subsequently identified as a vibration problem. It collects three kinds of information: 1) demographic data (age, gender, years of education, current smoking status), 2) the magnitude of 10 complaints on a linear analog scale (headache; nose, eye, and throat irritation; chest tightness, etc.), and 3) work characteristics (tenure at the institution and in the building; and hours per day in the building, in individual offices, and at computer screens). A copy is attached as the appendix. No characterization of the physical environment or further description of job tasks was undertaken.

Environmental Characteristics

Nine indoor air-quality characteristics were measured. The instruments and the associated minimum sensitivity are noted in Table 1. Temperature, relative humidity, light intensity, respirable suspended particulates (RSP), air velocity, and volatile organic compounds (VOC) were monitored using direct-reading instruments. The photoionization detector was calibrated to methane, and the manufacturer's correction factor for toluene was applied to all results. Carbon dioxide (CO_2) and formaldehyde levels were measured with direct-reading indicator tubes. Vibration was recorded on a strip chart and subsequent analysis of the chart was made to determine the acceleration. Respirable suspended particulates (RSP) were measured electronically using a meter containing a 3.5 m impactor and piezobalance. Where measurements were below the threshold of detection but registered a value other than zero, the threshold value was entered as a number for purposes of analysis.

The percentage of dissatisfaction attributable to the perception of draft was calculated according to equations developed by Fanger and Christensen (1986). Although this figure was developed to predict a population percentage of dissatisfaction, the authors assumed that the percentage figure might be used as a surrogate variable to explain the amount of dissatisfaction on an individual basis that could be attributed to temperature and airflow. The percentage figure was then used as a continuous variable in regression modeling.

The length of duct work leading to each office was calculated from building floor and engineering drawings. The building was divided into three zones, and the length of duct-work was entered as an ordinal variable (1 to 3), referred to as "duct." This was done by an engineer with no knowledge of the level of complaints in the individual offices.

TABLE 1

Instrumentation Characteristics

Parameter	Instrument	Minimum	Variability
Light	Sylvania D-2000	1 foot candle	+/− 5%
Temperature	Solomet MPM	0/60°C	+/− 0.3°C
Relative humidity	Solomat	0–100%	+/− 3%
Particulates	TSI 5500	10 ug/m³	+/− 1%
Airflow	Alnor Thermo-anemometer	20 feet per minute	+/− 3 fpm
Volatile Organic Compounds	Century 128 OVA	0.1 ppm	+/− 0.1 ppm
Carbon Dioxide	Draeger tubes	300 ppm	+/− 35%
Formaldehyde	Draeger tubes with activator extender tubes	0.04 ppm	+/− 35%
Vibration	Kinematics VM-1 Fotonic MT 1-Sensor	10 Hz	+/− 5%

Statistical Analyses

Data were analyzed using the Statistical Package for the Social Sciences for Microcomputers [SPSS/PC+]. All data were plotted. Where data were distributed lognormally, as suggested by viewing histograms, the transformed number was used in calculations (particulates and relative humidity). Results were accepted as statistically significant when the associated p-value was less than 0.05. Where p-values fell between 0.10 and 0.05, the differences were considered suggestive of an effect and worth closer scrutiny.

Because of several recent investigations (Skov et al. 1987; Hedge et al. 1987) symptoms were summed to two symptom complexes. "Eye irritation," "chest tightness," "pharyngitis," "nose irritation," and "difficulty breathing" were summed to "mucous membrane complaints"; "headache," "irritability," "nausea," "difficulty concentrating," "alertness," and "lethargy" to "systemic symptoms." The logarithm of the sums was used in analyses since variables were lognormally distributed.

The maximum number of available records was used in analyses of variance and in correlations through a standard SPSS/PC+ 2.0 command (missing = pairwise). Only records for which complete data were available were used in regression models. Because of multicollinearity and the number of missing measurements, there were severe restrictions on the number of variables that could be used in developing regression models. The number of variables in each model was restricted so that there were always approximately five times as many complete records available for that analysis as independent variables to avoid overparameterization. Where the zero-order correlation coefficient between two variables was greater than 0.25, only one of the variables was used in any given model.

Environmental measures were examined for their correlation. Zero-order correlation coefficients between symptoms and both demographic variables and exposure measures were obtained. Analyses of variance were then performed using gender and current smoking status as main effects and symptoms and environmental measures as outcome variables to examine the distribution of variables. Finally, multivariable regression models were developed using the symptom categories as dependent variables. For all analyses, first simple and then stepwise models were obtained, using the same structure for mucous membrane and systemic symptoms (dependent symptoms). Only variables that did not demonstrate multicollinearity were used as independent variables in regression models. First, the relationship was explored between the level of symptoms and demographic characteristics (age, education, gender, and current smoking status) and work habits (hours spent at various tasks and in various parts of the building). Second, the same analyses were performed using environmental characteristics (temperature, relative humidity, carbon dioxide, velocity of air, acceleration, noise levels, and lighting). These two sets of models are not presented. Because of the large number of missing values and questionnaire responses, only 13 records had complete records to develop models that included all variables of interest, so that these models could not be viewed as legitimate endeavors.

Finally, models were developed for the factors that have

TABLE 2

Environmental Characterization

		Mean	Median	Standard Deviation	Total # Available	Range
Relative Humidity (%)		35.5	34.8	8.3	90	19.3–65.0
75th, 90th, and 95th percentiles:	40.8, 45.3, 50.0					
% at or below the limit of detection:	0%					
Temperature (°F)		74.5	74.3	2.8	105	62.7–81.3
75th, 90th, and 95th percentiles:	76.4, 77.0, 80.1					
% at or below the limit of detection:	0%					
Airflow velocity (ft/min)		25.0	24.0	5.5	84	nd–43.0
75th, 90th, and 95th percentiles:	27.0, 34.0, 38.0					
% at or below the limit of detection:	20 (24%)					
Carbon dioxide (ppm)		820	800	201	102	300–1250
75th, 90th, and 95th percentiles:	1000, 1070, 1100					
% at or below the limit of detection:	0 (0%)					
Respirable suspended particulates (mcg/m^3)		36	30	15	103	nd–90
75th, 90th, and 95th percentiles:	40, 60, 68					
% at or below the limit of detection:	20 (21%)					
Light (foot-candles)		42.0	38.5	25.1	100	2.0–150
75th, 90th, and 95th percentiles:	52.0, 69.5, 89.5					
% at or below the limit of detection:	0, (0%)					
Noise (decibels on the A-weighted scale)		58.3	55.0	8.9	79	50.0–85.0
75th, 90th, and 95th percentiles:	60.0, 68.0, 85.0					
% at or below the limit of detection:	0 (0%)					
Vibration (Herz)		10.3	10.0	8.9	72	nd–19.9
75th, 90th, and 95th percentiles:	10.0, 10.0, 12.0					
% at or below the limit of detection:	68 (94%)					
Formaldehyde (ppb)		64.4	40.0	131	55	nd–1000
75th, 90th, and 95th percentiles:	40, 64, 152					
% at or below the limit of detection:	40 (73%)					
Volatile organic compounds (ppm)		0.63	0.600	0.30	30	nd–1.00
75th, 90th, and 95th percentiles:	1.0, 1.0, 1.0					
% at or below the limit of detection:	3 (10%)					

TABLE 3

Environmental Characteristics: correlation matrix[1]

	RSP[1]	Tempera-ture	Airflow Velocity	Relative Humidity	Carbon Dioxide	Volatile organic compounds	Formalde-hyde	Lighting	Sound	Acceleration
Temperature	.029 90									
Airflow velocity	−.113 84	−.310** 84								
Relative humidity	.366** 90	.018 90	.310** 77							
Carbon dioxide	.330** 102	.352** 102	.045 84	.481** 98						
Volatile organic Compounds	−.515** 29	−.700** 30	−.116 11	−.594** 21	−.627** 28					
Formaldehyde	.109 55	.303* 55	−.024 45	.031 52	.140 55	−.094 15				
Light intensity	−.002 99	−.198* 100	−.041 80	−.050 86	.137 98	−.155 29	.637** 55			
Sound level	−.102 77	−.552** 79	.639** 59	.114 71	−.013 76	−.597** 25	−.092 48	−.025 78		
Acceleration	.236* 72	−.096 61	.227 72	.022 64	−.083 72	.068 17	.002 35	−.091 71	−.091 51	
Draft[3]	−.218* 84	−.338* 84	.937** 84	.230* 77	.058 84	−.088 11	−.029 45	−.028 80	.662** 59	.063 64

1: Each cell contains the coefficient and the number of records from which that coefficient was calculated.
2: RSP = log (respirable suspended particulates)
3: draft calculated from Fanger and Christensen (1986)
*: $p < 0.01$
**: $p < 0.001$

been considered of greatest interest, again for both systemic and mucous membrane symptoms. Only these models are presented in the tables. Because of the interrelationship of temperature, airflow velocity, and relative humidity and the non-random distribution of these parameters in the analyses of variance, and their contribution to some of the regression models using only environmental parameters, the "perception of draft" was used in the final models.

Simple and backward-stepping models (p(out) = 0.1) were developed using all variables. In forward-stepping models (p(in) = .05), gender and smoking status were forced as indicator variables; subsequently the other variables were allowed to enter. All models were developed both with and a second time without the duct variable.

RESULTS

Measurements of volatile organic compounds and formaldehyde were discontinued after two weeks, since the instruments had been rented only for that period, and initial review of the data revealed levels only in the range of 0.5 to 1.5 ppm for VOC (n = 30) and consistently less than 0.04 ppm for formaldehyde (n = 55). Because of travel, illness, and mobility of the population, questionnaires were available only on 105 (67.75%) of all eligible individuals. Because of instrumentation difficulties and incomplete questionnaire responses, not all records could be used in each comparison. Only 13 had complete records for all questionnaire responses and all measured variables. Only 73 (68.9%) had complete questionnaires and measurements of RSP, thermal parameters, lighting, and noise.

Table 2 summarizes the distribution of environmental characteristics. Relative humidity, temperature, and airflow were generally in the acceptable range for office work. No carbon dioxide levels exceeded 1250 ppm. RSP concentrations were all less than 100 $\mu m/m^3$. Only one measurement of light intensity exceeded 100 fc at the desk level. Noise was generally acceptable for office work. No levels of VOC exceeded 1 ppm. Plotting the data revealed that particulates and relative humidity were lognormally distributed, so that those variables were transformed and the transformed values used in further calculations. Table 3 presents the correlation matrix for environmental measures. The levels of many of the variables were related. The associations were generally complex, but generally expected. There was a meaningful relationship between levels of RSP, VOC, and CO_2: as effective local ventilation increased, RSP and VOC concentrations decreased. Temperature was directly related to both VOC and CO_2 concentrations, implying again that as local ventilation effectiveness increased, temperature was controlled better and VOC concentrations decreased. Nevertheless, several relationships imply surprising effects: a significant relationship between the noise level and temperature, airflow velocity, and VOC concentrations clearly demonstrates the entanglement of the individual parameters. The duct variable was not associated with any variables.

No correlation was seen between the level of symptoms and age, years of education, duration of employment at the institution or the building, time spent in offices, or time spent at computers. Similarly there were no statistically significant relationships between either symptom grouping and any of the environmental measures. The only non-randomly distributed factor detected was that women tended to sit farther downstream along the ventilation ducts (chi-square = 9.68; 2° of freedom: $p < 0.01$). There was no overall relationship between the length of duct work leading to an office and symptoms.

Table 4 summarizes demographic characteristics, work habits, level of symptoms, and air quality parameters for smoking and non-smoking women and men. There was no difference in age or education between gender or smoking

categories. Men complained of increased levels of mucous membrane symptoms ($p < 0.10$), sat closer to air-conditioning units ($p < .02$), and were subjected to higher levels of RSP ($p < 0.1$) and noise ($p < .1$) than women. Women worked longer hours elsewhere in the building outside of their own offices ($p < .1$) and were exposed to higher concentrations of volatile organic compounds ($p < .02$) than men. Smokers did not complain of higher levels of mucous membrane symptoms ($p > 0.10$) but were exposed to higher concentrations of RSP ($p < .01$) and lower air velocity ($p < .1$) than nonsmokers, who in turn were subjected to higher levels of noise pollution ($p < .1$). Male smokers had begun working more recently at the institution ($p < .1$) but not at the building, worked more hours at computers ($p < .02$), and had less airflow at their workstations ($p < .02$). They had the highest levels of RSP ($p < 0.01$). They also complained of more mucous membrane symptoms than did any other subgroups ($p < .03$). Although VOC were not randomly distributed, their pattern did not fit that of the complaint levels, so no simple relationship between them and complaints may be construed.

Regression models demonstrated significant relationships between environmental exposures but not demographics. Gender, age, years of schooling, length of employment at the institution and in the building, and duration of time spent at their own desk and at computers were unrelated to the level of complaints. In models with exposure measures alone, using only non-collinear variables, RSP, temperature, and relative humidity generally contributed to the models. The coefficient for light intensity often approached statistical significance, but never at the .05 level.

Table 5 presents the results of four models for mucous membrane symptoms as dependent and known factors of interest as independent variables. Because air velocity, relative humidity, and temperature showed some relationship to the level of complaints in models developed using each one separately, regression models for environmental characteristics were developed using the "prediction of draft" variable. Additionally, because of the uneven distribution of males and females along the duct distance, all models were run with and without the "duct" variable. In the simple models, the only variable to consistently and spontaneously enter all four equations was the concentration of RSP. When the sex variable was forced into the forward-stepping model, the duct variable no longer contributed any significant information, although in unforced models the duct variable was a stronger predictor. Smoking status was never clearly associated with the development of symptoms, although associated p-values were generally between .1 and .05. Lighting intensity contributed to two of the models.

In models examining systemic symptoms, RSP were again the strongest predictor of complaints. Smoking status was consistently unrelated, in contrast to mucous membrane symptoms, where there was at least an association. The distance from the air-handling unit, i.e., the duct variable, was also consistently unrelated to symptoms. In two models, light intensity contributed significantly. Interestingly, the sex variable approached statistical significance in all four models, although there was no clear gender effect visible in the analyses of variance.

Most interestingly, carbon dioxide levels failed to demonstrate a consistent significant relationship to either symptom category in any of the equations. When the models were run substituting CO_2 for the ordinal "duct" variable, no substantial difference was noted in the other variable coefficients.

DISCUSSION

The results seen in this cross-sectional study in a single building are consistent with results recently presented elsewhere, namely that complaints attributed to indoor air may in fact be related to specific environmental exposures. On the other hand, carbon dioxide alone was not an indictor of the level of complaints, either across buildings or within a single building.

First, RSP were the strongest predictors of complaints in this data set. Three large cross-sectional studies, without personal sampling, have suggested that IAQ complaints may have a cause. Two (Finnegan et al. 1985; Burge et al. 1987) suggest that they may be related to mechanical ventilation and, specifically, chilling. The third (Skov et al. 1987) suggests that dust aspects may contribute substantially. Fanger et al. (1988) demonstrated that indoor air quality complaints in a series of 20 buildings in Copenhagen were related to several parameters. They attributed approximately 40% of the pollutant load to the ventilation system, approximately 20% to office furnishings, and only 15% to the building occupants. A recent study (Sterling et al. 1987) suggested that indoor air quality is independent of environmental tobacco smoke (ETS). Several subsequent contributions (Repace and Lowrey 1987; McCunney and Caskins 1988) suggest the answer may not be as firm as the authors would like, since anecdotal reports do support a possible connection. In fact, Fanger et al. (1988) have demonstrated that approximately 20% of the pollutant load as perceived by panels of arbiters may be related to ETS. There was no clear evidence that complaints were related to smoking status, although in a data set of this size, failure to demonstrate a significant relationship may well be due to a type-two error.

Other sources of RSP exist in the indoor environment. A case of palpable purpura from a photoactive copy machine has been reported (Tencati 1982). At a northeastern university a case of allergic rhinitis has recently been attributed to printed laser jet printer paper (Skoner, personal communication). Although no published reports are available to demonstrate contamination of duct linings as a major contributor to indoor air quality problems, the idea has been discussed for several years at conferences. The possible relationship of complaints to the distance from the air-handling units may be interpreted as suggesting that the length of ventilation ducts (in this case unlined) contributed to complaints. On the other hand, given the unequal distribution of males and females along the length of ducts, we cannot address the issue with certainty. RSP in buildings may accumulate from ETS, from office machines such as laser jet printers and photocopying machines, and from contaminated duct linings. We are not certain of the source of the dust in this study. Electron microscopic analysis of several dust samples suggested it was a collection of fibers from insulation, environmental tobacco smoke, and spores. Thermal parameters were also related to symptoms, although draft was not. One possible interpretation is that the thermal conditions are not important for humans but, for example, for microorganisms. In any case, future investigations of indoor air quality should focus on respirable and total suspended particulates as serious contributors to indoor air quality complaints.

Interestingly, female gender and educational level failed to predict complaints clearly. Skov et al. (1987) and Burge et al. (1987) both demonstrated a mildly increased rate of complaints among women. This also is consistent with prior studies (Gamble et al. 1986) presented at this meeting. Never-

TABLE 4

Demographics, Symptom Levels, and Environmental Parameters by Smoking and Gender Groups

NS = non-smoker
S = smoker

	WOMEN[1]		MEN[1]		F-Value			
	NS	S	NS	S				
Number available	53	12	29	12	Gender[2]	Smoking[2]	Interaction[2]	Explained[2]
DEMOGRAPHICS								
Age (years)	30.2 (1.0)	29.7 (2.2)	31.9 (1.7)	35.5 (6.4)	1.544 (0.217)	0.347 (0.55)	0.683 (0.410)	0.926 (0.431)
Education (years of school)	16.4 (0.4)	15.0 (0.5)	15.2 (0.6)	15.6 (0.8)	1.747 (0.188)	0.647 (0.423)	0.730 (0.191)	1.463 (0.229)
Duration of employment at the:								
institution (years)	3.2 (0.3)	4.9 (1.3)	3.1 (0.4)	2.4 (0.5)	1.305 (0.256)	0.865 (0.355)	3.086 (0.082)	1.684 (0.175)
building (months)	20.2 (1.6)	22.4 (3.7)	17.0 (2.8)	17.3 (3.0)	2.430 (0.122)	0.231 (0.632)	0.135 (0.714)	0.882 (0.453)
Hours in: office	4.9 (0.3)	5.0 (0.5)	5.6 (0.4)	5.3 (0.9)	1.289 (0.259)	0.017 (0.895)	0.067 (0.797)	0.452 (0.716)
Duration of employment at the:								
building	2.8 (0.4)	3.2 (0.5)	1.9 (0.7	1.6 (0.2)	2.430 (0.122)	0.231 (0.632)	0.135 (0.714)	0.882 (0.453)
at a computer	4.2 (0.3)	3.5 (0.5)	2.8 (0.4)	5.0 (1.1)	1.882 (0.173)	1.041 (0.310)	5.999 (0.016)	2.885 (0.039)
SYMPTOM SCORES								
Mucous Membrane Symptoms								
log (sum of mucous membrane symptoms)	1.86 (0.06)	1.73 (0.16)	1.90 (0.09)	2.31 (0.14)	2.817 (0.096)	0.892 (0.347)	5.397 (0.022)	3.163 (0.028)
DIFFUSE SYMPTOMS								
log (sum of diffuse symptoms)	1.91 (0.07)	1.86 (0.16)	1.97 (0.11)	2.25 (0.15)	1.599 (0.299)	0.606 (0.438)	1.756 (0.188)	1.399 (0.248)
ENVIRONMENTAL PARAMETERS								
relative humidity (%)	34.1 (1.3)	34.8 (1.8)	36.3 (1.7)	40.4 (2.6)	2.964 (0.089)	1.200 (0.276)	0.726 (0.397)	1.709 (0.159)
temperature (° Fahrenheit)	74.6 (0.4)	74.8 (0.9)	73.9 (0.5)	75.1 (0.6)	0.702 (0.404)	1.008 (0.318)	0.547 (0.461)	0.698 (0.555)
velocity (feet/minute)	23.5 (1.4)	23.9 (1.4)	25.6 (1.4)	15.6 (3.6)	0.066 (0.798)	3.278 (6.074)	6.327 (0.014)	3.326 (0.026)
carbon dioxide (parts per million)	787 (30)	875 (46)	851 (38)	827 (49)	0.843 (0.361)	0.596 (0.442)	1.357 (0.247)	0.981 (0.405)
particulates (ug/m^3)	31 (0.1)	36 (0.5)	34 (0.2)	50 (0.8)	3.227 (0.075)	8.303 (0.005)	2.339 (0.129)	5.006 (0.003)
formaldehyde (parts per billion)	90 (38)	60 (20)	40[7] —	40[7] —	1.548 (0.219)	0.114 (0.737)	0.092 (0.763)	0.582 (0.629)
volatile organic compounds (parts per million)	0.75 (0.06)	0.60* —	0.40 (0.15)	0.57 (0.01)	6.962 (0.014)	0.437 (0.515)	0.949 (0.339)	2.743 (0.063)
lighting (footcandles)	46 (4)	38 (6)	38 (3)	36 (2)	1.300 (0.257)	0.861 (0.357)	0.172 (0.679)	0.834 (0.47)
noise level (dBA)	58 (1)	55 (1)	62 (2)	56 (2)	3.324 (0.072)	3.063 (0.084)	0.479 (0.491)	2.145 (0.102)
acceleration (Herz)	4.09 (0.70)	3.21 (0.69)	3.13 (0.36)	3.48 (1.35)	0.476 (0.493)	0.166 (0.685)	0.437 (0.511)	0.384 (0.765)

1: Numbers in parentheses are standard errors
2: Numbers in parentheses are p-values
1, 2: One way analysis of variance for groups main effects with interactions (gender smoking)
*: only one value available for calculation

TABLE 5

Results of regression models for mucous membrane symptoms as the dependent variable

Variable	Model: simple	simple (without duct variable)	stepwise backward	stepwise forward (forcing sex and smoking)
Adjusted R-squared	.256	.115	.266	.113
p-value	.02	.15	< .01	< .1
Variables				
Sex	−1.38	.486	—	.43
Smoking	1.771+	1.34	1.78+	1.01
Duct length	3.001**		2.35*	—
Log RSP	−3.145**	−2.31*	−3.28**	−2.76**
Draft	0.610	−.82	—	—
Formaldehyde	0.912	.21	—	—
Lighting	2.250*	.94	2.04*	—
Sound	0.391	1.10	—	—

+ $p < 0.100$
* $p < 0.050$
** $p < 0.010$

Draft = 13800 {[(airflow velocity − 0.04)/(temperature − 13.7) + 0.0293]^2 − 0.000857};
RSP = respirable suspended particulates (microgram/m^3);
Duct = an ordinal variable (1, 2, 3) for distance from the central air-handling unit that served that individual room;
RH = relative humidity;
form = formaldehyde concentrations (in ppm);
light = light intensity (foot-candles);
sound = sound pressure level (decibel on the dBA scale)

TABLE 6

Regression models using systemic symptoms as dependent variables

	Model: Simple	Simple (without duct variable)	Stepwise backward	Stepwise forward (forcing sex and smoking)
Adjusted R-square	.233	0.259	.286	.318
	<.04	<.02	<.01	<.01
Sex	1.77+	1.85+	1.70+	1.94+
Smoking	1.50	1.56	—	1.60
Duct length	−.09		—	—
Log RSP	−3.53**	−3.64**	−3.93**	−4.32**
Draft	.52	.52	—	—
Formaldehyde	0.22	.20	—	—
Lighting	1.46	1.64	2.22**	2.64*
Sound	−.13	−.15	—	—

+ $p < 0.100$
* $p < 0.050$
** $p < 0.010$

Draft = 13800 {[(airflow velocity − 0.04)/(temperature − 13.7) + 0.0293]^2 − 0.000857};
RSP = respirable suspended particulates (in microgram/m^3);
Duct = an ordinal variable (1, 2, 3) for distance from the central air-handling unit that served that individual room;
RH = relative humidity (in %);
form = formaldehyde (in ppm);
light = light intensity (in foot-candles);
sound = sound pressure level (decibels on the dBA scale)

theless, those studies merely requested information on the presence and frequency of complaints, not on their intensity. Assumptions that women or less educated "pink-collar" workers complain more than traditional "white-collar" workers or those with higher education could not be substantiated in this study, since the authors did not ask about the presence but merely about the intensity of complaints. It is not implied that women complain less than men or that psychodynamic and ergonomic factors are uninvolved. Well-designed studies have demonstrated their importance, and the topic is discussed elsewhere in this symposium. The authors simply wish to point out that the level of indoor air quality complaints may in fact be associated with specific environmental characteristics (elevated RSP, lighting, and possibly thermal parameters). Video display terminal (VDT) operators may have similar exposures to air pollutants as their colleagues. Nevertheless, until specific sampling is done to demonstrate that the exposures of women in offices (who are much more frequently VDT operators than their male colleagues) are the same as those of males, the excess complaint rate among

women may be attributed to other factors in addition to their gender.

Carbon dioxide, the parameter most often cited as an indicator of poor ventilation and, at least in the past, used as an indicator of inadequate fresh air provision, did not seem related to complaint levels. This has been pointed out by others (Berglund et al. 1987). This result was elegantly explained by Fanger et al. (1988), who demonstrated that humans and ETS, the primary sources of CO_2, contribute less than 40% of the perceived pollution load in buildings. It is therefore not surprising that no relationship was found.

We are unable to discuss the relationship of our results with those presented by Molhave et al. (1986) for two reasons. First, there were few records in this data set that contained both VOC and RSP. Even in the small sample obtained, there was a statistically significant relationship between VOC and RSP, so that it would not have been legitimate to develop regression models containing both variables. Second, some authors feel that the method used here to measure RSP may in fact be sensitive to the concentrations of VOC where the RSP concentration is low. VOC may simulate the presence of particles through a site-specific "particle production" effect, which occurs locally on the piezobalance itself. This pilot study should therefore not be interpreted as evidence against the VOC hypothesis. On the other hand, no relationship between formaldehyde exposures and the level of symptoms was seen, either in zero-order correlations or in regression models. Only five records contained values that exceeded the minimum detectable levels. This study alone therefore may not be used to discount the importance of formaldehyde and other VOC, specifically since recent studies (Ritchie and Lehnen 1987; Horvath et al. 1988) have demonstrated a higher prevalence of mucous membrane symptoms at formaldehyde concentrations of less than 0.5 ppm and there is some literature suggesting neuropsychological deficits in laboratory technicians and mattress workers may arise from as yet unspecified concentrations.

At least one prior study has suggested that complaints attributed to indoor air quality are indistinguishable from and may be attributed to lighting. Sterling and Sterling (1983) demonstrated that a change in fluorescent lighting may reduce the level of complaints among office workers in the same way as increased provision of outside air. There was a high degree of collinearity between the individual symptoms so that it may not be possible to attribute symptoms of one category solely to an exposure that could be expected to lead to the symptoms. Such a spillover effect has been documented previously (Stellman et al. 1985). Other additional factors such as the thermal parameters that could not be adequately examined in this study, ergonomic issues, and psychosocial measures may interact with RSP and lighting to contribute to the overall comfort in indoor environments.

No pilot study will provide results that may be generalized to the population of sick buildings or to the problem of any air quality-related complaints as a whole. Several results are not inconsistent with prior literature, i.e., the relationship of RSP and lighting with complaints, but should not be overinterpreted at the present time, although they should be clearly considered when designing further studies. Other findings, e.g., the lack of excess symptoms in women or the possible association of duct work with symptoms, have not been seen in the past and must be replicated before they are discussed seriously. This pilot study does suggest, as have prior studies, that the sick building syndrome is not due solely to "inadequate ventilation." It presents a method that may be useful for relating the level of complaints to levels of specific air quality parameters that may prove useful in identifying the actual cause of the rampant complaints among office workers. This method may in fact allow the development of dose-response relationships between exposures and effects. Obviously the study design must be replicated in a larger series of buildings, unselected for the presence of complaints, before the results may be considered important. Until others have replicated the results, one may not assume a true, generalizable relationship. A study using the same methodology in five buildings unselected for the presence of complaints is currently in progress (Hodgson et al. 1989).

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DISCUSSION

Carl N. Lawson, LRW Engineering Inc., Tampa, FL: Were there any stress problems that were related to the project?

M.J. Hodgson, University of Pittsburgh School of Medicine, Pittsburgh, PA: This was an extraordinary building and the occupants were computer scientists in industry consulting jobs, i.e., "soft money" positions, administrative staff (managers, secretaries), and some computer technicians. I have no reason to believe that they were completely happy with their work—they had had complaints for almost two years.

Ed Light, Biospherics, Beltsville, MD: Was the broader study associating occupant complaints with the building completed?

Hodgson: Several engineering studies were conducted in the building. Rebalancing of the system and modifications were undertaken. No attempts have been made to investigate symptoms after these modifications.

William A. Turner, Harriman Associates, Auburn, ME: Back calculating based on present CO_2 levels of 1000 ppm, 140 people, and 50,000 ft^2 suggests low occupant density (three people per 1000 ft^2) less than 7 cfm O.A. per person, and less than .3 ach O.A. Would you characterize this building as a poorly ventilated building with cooling load problems, though meeting suggested ASHRAE 62-1981 ventilation guidelines?

Hodgson: Yes, that is a reasonably apt characterization, although the CO_2 levels were on average lower than 1000. At times, substantially more individuals (up to 100 students using computer labs) occupied the building. There were major problems with ventilation effectiveness.

Lee Hathon, Rocky Mountain Center for Occupational and Environmental Health, University of Utah, Salt Lake City: When designing a questionnaire, should the investigator attempt to uncover if any of the symptoms may be behaviorally induced by workplace stress?

Hodgson: "Workplace stress" is a poorly defined term in this context. Most outbreaks of occupational disease have some contribution of emotional distress. The purpose of identifying organizational stressors and psychological distress varies. In research settings, both are important. When attempting to identify causes of complaints in buildings, those factors must also be identified because if they contribute to the problem, they must be dealt with appropriately if the problem is to be resolved.

HEALTH EFFECTS OF HEATING WITH WOOD: CHEST ILLNESS IN YOUNG CHILDREN AND INDOOR HEATING WITH WOODBURNING STOVES

J.S. Osborne, III, Ph.D., M.P.H. R.E. Honicky, M.D.

ABSTRACT

This study investigated a suspected relationship between the occurrence of chest illness in young children and use of woodburning stoves (WBS) for indoor heating. Data were prospectively collected during the winters of 1980, 1981, and 1982 for 62 mid-Michigan children age one to seven years (31 randomly selected children from WBS-heated homes and 31 controls from homes heated by conventional sources matched for age, sex, and place of residence). The specific a priori *research hypotheses were that the proportion of children having a chest illness would be significantly greater in the WBS group than in the control group, that a greater proportion of WBS group children would have chest illnesses lasting at least one week, and that a greater proportion of WBS group children would be hospitalized before age two years for chest illness.*

Results showed a significant difference ($p < 0.05$) between the WBS and control groups in the proportion of children having a chest illness from 1980–1982 (especially bronchitis, upper respiratory infection, and pneumonia); 39% of the WBS group and 19% of controls had at least one such illness. Further, the WBS group had a greater proportion of chest illnesses lasting at least one week (32% vs. 16%) and a greater proportion of hospitalizations for chest illness before age two years (16% vs. 10%). These differences were not accounted for by medical histories, frequency of physician visits, sociodemographic factors, or exposure to other sources of indoor air pollution investigated in the study (i.e., parental smoking, cooking with gas, urea-formaldehyde foam insulation) and suggest that indoor heating with WBS may be a significant risk factor for chest illness in young children.

INTRODUCTION

The indoor environment is a significant factor in the health of modern populations. Data indicate that urban residents in the United States spend more than 90% of their time indoors and that a majority of the population spends more than 80% of its time indoors. Accompanying this demographic transition has been an increasing concern regarding the quality of indoor air and the presence of hazardous pollutants, whose concentrations are sometimes higher indoors than they are outdoors (Spengler and Sexton 1983; Task Force on Epidemiology of Respiratory Diseases 1980).

The problem of controlling indoor exposures to airborne hazards to the respiratory system has been emphasized by the Task Force of the National Institutes of Health (NIH) on Prevention, Control, and Education for Respiratory Diseases (1977) and by the NIH Task Force on Epidemiology of Respiratory Diseases (1980). While the Task Force reports indicate that the relationship between bronchial asthma and a variety of agents is well-established clinically, this is not true for relationships between other prevalent respiratory problems and exposures to domestic sources of airborne pollutants, many of which result from the application of technologies in the home.

The presence of recurrent pneumonia, bronchitis, upper respiratory infection, wheezing, and tachypnea (rapid shallow breathing) in young children is commonly associated with a family history of atopy, parental smoking, home cooking fuel, or recurrent exposure to viral illnesses in siblings of school age (Bonham and Wilson 1981; Cameron et al. 1969; Colley 1971, 1974; Colley et al. 1974; Glezen and Denny 1973; Leeder et al. 1976; Luguette et al. 1970; Melia et al. 1977; Monto et al. 1971; Norman-Taylor and Dickinson 1972; Speizer et al. 1980). Earlier epidemiological studies on the patterns of occurrence and etiology of respiratory infection in the family related frequency of illness to age, sex, and sociocultural factors such as family size and crowding (Brimblecombe et al. 1958; Dingle et al. 1964; Lidwell and Sommerville 1951). One possible etiological factor that is neither commonly elicited in medical histories nor well documented in the literature is use of a woodburning stove for indoor heating.

An increasing number of families in the United States are converting to woodburning stoves in an effort to reduce their winter heating bills. Estimates indicate that more than one million new woodburning stoves are sold for domestic use in the United States each year and that usage is increasing in all socioeconomic groups (Lipfert and Dungan 1983; Meyers and Schipper 1984; Thompson 1984). The three basic types of woodburning stoves are: freestanding units, fireplace-insert units, and furnace add-on units. Documented hazards associated with the use of woodburning stoves include accumulation of carbon monoxide (especially in newer, more airtight homes) as well as burn injuries and fires (Breysse 1981; Remensnyder and Gryska 1981).

Although several types of woodburning stoves are in use, most of them function similarly to the most popular type—the Franklin stove, invented by Benjamin Franklin in Philadelphia in the 1740s (Harrington 1979; Schneider 1980). The Franklin-type stove operates as a contained combustor of wood, releasing a variety of pollutants into the indoor environment (Butcher and Sorensen 1979; Cooper 1980; Cooper and Malek 1982; Lipfert and Dungan 1983; Moschandreas et al. 1980). While technological advances have reduced emissions to some degree, even the most efficient woodburning stoves emit hazardous pollutants which are released directly

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into the home when the stove is operating and the door is opened to add wood. Therefore, the question arises as to whether by-products of wood combustion are accumulating in homes where woodburning stoves are used as a source of heat. This issue is especially important when one considers the trend to increase home insulation and overall airtightness in an effort to conserve energy and reduce heat loss (Breysse 1981; Moschandreas et al. 1980).

During the winter of 1980 clinical observations at the Pediatric Chest Clinic of the Michigan State University Clinical Center suggested an increase in the number of preschool children presenting with lower respiratory tract illness whose history included use of a woodburning stove for indoor heating. In several of these children there were no discernible coexisting factors.

The present study was conducted to investigate whether there was a difference in the occurrence of chest illness for young children from homes heated by wood and by conventional means. The specific *a priori* research hypotheses were that the proportions of children having at least one chest illness per year, having chest illness lasting at least one week, and needing to be hospitalized for chest illness before age two years would be greater for children from homes heated by woodburning stoves than for those from homes heated by furnaces or electricity.

METHODS

The population from which samples were drawn for this study consisted of 9977 children one to seven years of age (as of January 1, 1982) who had attended the Michigan State University Clinical Center for well-checks and physicals, immunizations, or illness care between 1976 and 1981 (inclusive). The Clinical Center offers both primary and subspecialty care and is essentially equivalent to a group practice setting for the pediatric population. Sixty-two children who lived within the five-county Greater Lansing area were randomly selected from this population without regard to reason for visit or primary diagnosis at clinic attended. The children were classified at the time of selection according to the type of indoor heating used in their home. Sampling proceeded until 31 children from homes heated by a woodburning stove had been selected and then continued until each child in the study group was matched for age, sex, and geographic area of residence with a child from a home heated by conventional means (i.e., gas furnace, fuel oil furnace, or central electric heat). The latter group of children constituted the "internal comparison" or "control" group.

The design employed was a "historical prospective design" (also referred to as a "retrospective-cohort design"), wherein the two groups stratified at selection by type of indoor heating were followed forward in time to determine their illness experience during the three-year period from 1980 to 1982 (Hulley and Cummings 1988; MacMahon and Pugh 1970; Mausner and Kramer 1985). The purpose in matching children in the study and control groups for age, sex, and geographic area of residence was to control for the potentially confounding effects of these variables.

Participants were recruited by a telephone call to their parents, who were informed that the study was being conducted to investigate the occurrence of chest illness in young children from homes with different types of indoor heating; all parents contacted participated in the study. The sample size of 31 subjects in the study and control groups was arrived at based on the intended method of analysis at the 0.05 level of significance. The 62 children in the study all lived within 40 miles of Lansing, MI, were between one and seven years of age (mean, 3.5 years), and were predominantly white (97%); 60% were boys and 40% girls.

Parents of the children were interviewed by telephone using an interview schedule modified from the Epidemiology Standardization Project Children's Questionnaire (Ferris 1978). The questions were self-explanatory and required a yes, no, or number response. Open-ended discussion by parents was permitted during the interview, supplementing information acquired through the closed-ended questions. Interviews were conducted randomly across both groups and respondents were the subjects' mothers in all but one case; the interviewer was not aware of group membership (prior to conducting the interview). Sociodemographic data, frequency of physician visits, medical histories, use of humidifiers and air filters, and exposure to domestic sources of indoor air pollution were also collected.

Data were analyzed to determine the proportion of children having at least one chest illness per year, having chest illnesses that lasted at least one week, and being hospitalized for chest illness before age two years. These outcomes were compared in the study and control groups using the nonparametric test of difference between proportions.

The study and control groups were also compared in terms of medical histories, socioeconomic status, frequency of physician visits, use of humidifiers and air filters, and exposure to three sources of domestically produced indoor air pollution which have been associated with chest illness and the occurrence of respiratory symptoms in young children. These exposures were parental smoking (and smoking in the home by other household members), cooking with gas, and having urea-formaldehyde foam insulation.

RESULTS

The occurrence of chest illness in the study and control groups was appreciably different (see Figure 1). Results showed a significant difference ($p < 0.04$) in the proportion of children having at least one chest illness per year, with twice the proportion in the study group as in the control group (see Table 1). Thirty-nine percent (39%) of children from homes heated by wood had at least one such illness per year compared with 19% of controls, the most commonly reported illnesses being bronchitis, upper respiratory infection, and pneumonia.

The study group also had twice the proportion of chest illnesses lasting at least one week—32% compared with 16%. With respect to hospitalization, 67% more children from homes heated by wood were hospitalized for severe chest illness before age two years—16%, compared to 10% of controls. Further, 40% of children requiring hospitalization in the study group had more than one such episode while none of the control group children were hospitalized for severe chest illness more than once. While differences in the proportions of children with chest illnesses lasting at least one week and requiring hospitalization before age two years were clinically significant, they were not statistically significant at the 0.05 level.

About three-fourths of homes (77%) in the study group used wood as the primary source of indoor heating. Wood was the only source of heat in 13% of homes in the study group. Fifty-eight percent (58%) of woodburning stoves were installed within a major living area. The number of half-cords of wood burned during 1982 ranged from five to 25 with a mean of 12.8 half cords per home.

About three-fourths of homes (77%) in the control group

TABLE 1

Children with at Least One Severe Chest Illness per Year, Chest Illness Lasting at Least One Week, and Hospitalization Before Age Two Years for Severe Chest Illness: Proportions in Study (WBS) and Control Groups, Z-Statistic, and Significance of Differences.

Chest Illness	Proportion (%) WBS Group	Proportion (%) Control Group	Z Statistic	Significance of Difference
At Least 1 Severe Chest Illness/Yr	38.7	19.4	1.72	0.04
Chest Illness Lasting At Least 1 Week	32.3	16.1	1.51	0.06
Hospitalization Before Age 2 Yrs. for Severe Chest Illness	16.1	9.7	0.76	NS*

* NS = Not Statistically Significant.

used fuel oil or gas furnaces as the primary source of heat; the remainder heated with steam, hot water, or a built-in electric unit.

Analysis of socioeconomic status as reflected by number of bathrooms in the home (as a surrogate for household income) and education of head of household showed no statistically significant differences ($p > 0.05$) between study and control groups. In the study group, 58% had one to one-and-a-half bathrooms, 32% had two, and 10% had three or more compared with 52%, 38%, and 10%, respectively, in the control group. Regarding the highest level of education for head of household, comparisons of the study group to the control group were as follows: 26% in each group graduated from college or had post-graduate training, 29% (study

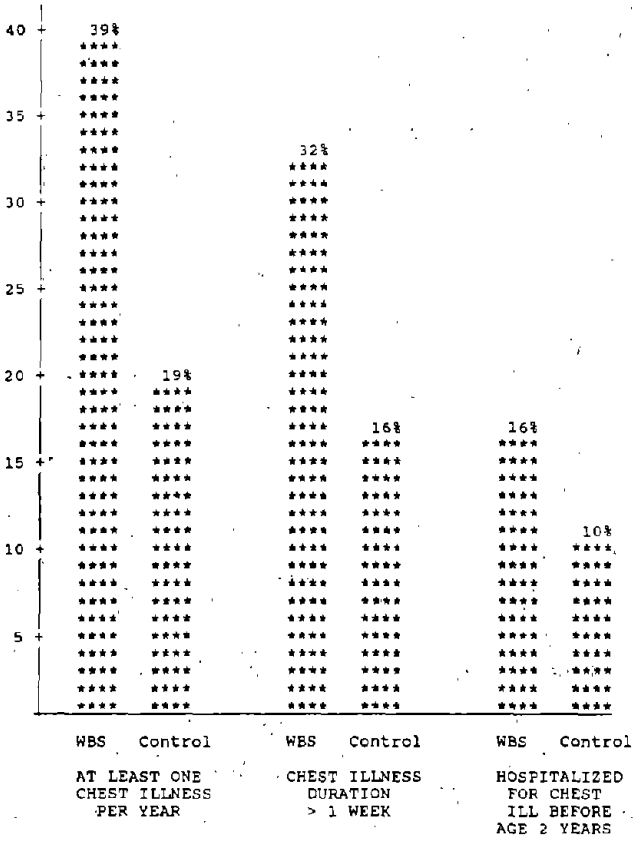

Figure 1 Proportions (as percent) of children with outcomes in study (WBS) and control groups

TABLE 2

Exposure to Parental Smoking, Cooking Fuel, Urea-Formaldehyde Foam Insulation, and Use of Humidifiers and Air Filters in Study (WBS) and Control Groups: Proportions (as percent), Z-Statistic, and Significance of Differences.

Exposure/Equipment	Proportion (%) WBS Group	Proportion (%) Control Group	Z Statistic	Significance of Difference
Parental Smoking*	48.4	51.6	−0.25	NS
Cooking Fuel:				
Gas	19.4	42.0	−1.99	0.02
Electricity	77.4	56.0	+1.66	0.05
Kerosene	3.2	0.0	+1.01	NS
Urea-Formaldehyde Foam Insulation	6.5	0.0	+1.47	NS
Humidifier(s) Used	48.4	48.4	0.00	NS
Air Filter(s) Used	25.8	9.7	+1.70	0.04

NS = Not Statistically Significant.

* At least one parent or other adult household member smoking tobacco regularly in the home.

group) vs. 23% (control group) had some college, 35% in each group graduated from high school, and 10% vs. 16% did not graduate from high school.

Medical histories of children and their parents indicated no clinical data which would predispose children in one group to a greater or lesser occurrence of chest illness than the other group. Frequency of physician visits was also not significantly different ($p > 0.05$), with a mean of three visits per child during the winter of 1982 among study group children compared with four visits among controls.

With respect to exposures and equipment known to affect indoor air quality, there were no significant differences between groups ($p > 0.05$) in parental smoking or use of urea-formaldehyde foam insulation (see Table 2). About half the homes in each group had at least one parent who smoked regularly in the home, with a slightly greater proportion in the control group (52% vs. 48% in the study group); the mean number of packs of cigarettes smoked per day by smokers in the study group was 1.8 compared with 1.5 in the control group. A small proportion of homes in the study group had urea-formaldehyde foam insulation. The control group made significantly greater use of gas stoves for cooking ($p < 0.02$; 42% vs. 19%) while a significantly greater proportion of the study group families cooked with electric stoves ($p < 0.05$; 77% vs. 58%) (see Table 2).

Regarding equipment which would tend to improve air quality, there was no difference ($p > 0.05$) in the use of humidifiers, with 48% of homes in each group using at least one humidifier regularly. However, the study group made significantly greater use of air filters ($p < 0.04$; 26% vs. 10%).

DISCUSSION

The major hypothesis of this study was that the proportion of children experiencing chest illness in homes heated by wood would be greater than the proportion in homes not heated by wood. In constructing the research design to test this hypothesis, particular attention was paid to controlling for potential confounding variables and sources of bias.

The potentially confounding effects of age, sex, and geographic area of residence (as a surrogate for outdoor air pollution levels) were controlled by matching subjects in the

study and control groups at selection. The potential effects of socioeconomic status, medical history, frequency of physician visits, cooking with gas, parental smoking, urea-formaldehyde foam insulation, humidifiers, and air filters were assessed in analysis.

Regarding possible selection bias and the representativeness of the samples, both well and ill children attend the ambulatory health care facility from which the samples were drawn. It is probable that more ill than well children present for care in the Pediatric Offices at the Clinical Center, as for any group pediatric practice. However, since most children present for yearly checks and preventive medicine, such as immunizations, as well as sick call (Behrman and Vaughan 1987), it is reasonable to assume that the samples are generally representative of young children receiving standard medical care living in south central Michigan.

Data were collected by telephone interview, which has the disadvantage that it can result in a lower reporting of illness frequency than actually occurs, a type of informant bias (Jordan et al. 1953; Monto et al. 1971; Monto and Ullman 1974). However, since a standardized instrument was used for data collection (i.e., the Epidemiology Standardization Project Children's Questionnaire), it is reasonable to expect that any underreporting of symptoms occurred to the same extent in both the study and control groups. In addition, participants were recruited for a general study of the effects of indoor heating (rather than a specific study of effects of heating with wood), thereby minimizing any informant bias which might be associated with a study of a particular type of indoor heating. Finally, the method of analysis favored the control group (i.e., made it more difficult to conclude there was a significant difference between groups) by comparing outcomes categorized as having occurred or not occurred rather than comparing mean number of episodes (which were considerably higher in the study group).

Several factors in the home have been associated in the literature with an increase in the frequency of recurrent respiratory tract illnesses in young children, especially parental smoking, cooking with gas, and urea-formaldehyde foam insulation. A number of studies have indicated that there is a greater occurrence of respiratory illness among children age five and older of smokers as compared with non-smokers (Bonham and Wilson 1981; Cameron et al. 1969; Luguette et al. 1970; Norman-Taylor and Dickinson 1972). There may also be a greater occurrence of bronchitis and pneumonia in the first year of life among children whose parents smoke as compared with children of non-smokers (Colley et al. 1974). Although the amount of tobacco smoked in subjects' presence was not recorded in the present study, the very similar distribution of cigarette smoking in the home (48% of parents from wood-heated homes, mean 1.8 packs/day; 52% of control parents, mean 1.5 packs/day) suggests that this factor probably did not play a significant role with respect to differences in the occurrence of chest illness in the two groups.

Children from homes in which gas is used for cooking have been found to have a greater occurrence of cough, "colds going to the chest," and bronchitis than children from homes where electricity is used (Melia et al. 1977; Speizer et al. 1980). Gas was used for cooking in a significantly higher proportion of homes in the control group. Therefore, while the greater use of gas stoves among controls may have been a confounding factor acting to reduce differences between groups, it seems reasonable to conclude that the part played by type of cooking fuel did not account for observed differences in the occurrence of chest illness.

Exposure to formaldehyde has been associated with a variety of detrimental effects, including symptoms of respiratory illness such as coughing and shortness of breath (Ashford et al. 1984; Grafstrom et al. 1983; Levin and Purdom 1983; Michigan Department of Public Health 1982; Nation's Health 1984; Sun 1984; Wildavsky et al. 1984). The very low number of homes with urea-formaldehyde foam insulation ($n = 2$) suggests that this factor did not have a significant effect.

It is of interest that the same proportion of homes in each group was equipped with humidifiers and that the study group made significantly greater use of air filters. This equipment would tend to decrease indoor concentrations of particulate pollutants and reduce respiratory tract irritation due to dry air. Despite the lack of humidity or particulate readings in the homes, the distribution of this equipment between groups suggests that differences in the occurrence of chest illness were not significantly affected by use of humidifiers or air filters.

The use of wood for space heating in the United States contributes significantly to outdoor levels of pollutants (especially particulates) in many residential areas (Cooper 1980; Lipfert and Dungan 1983; Sexton et al. 1986). The use of fireplaces and woodburning stoves in the home has also been shown to increase indoor levels of various pollutants (Cooper and Malek 1982; Moschandreas et al. 1980; Sexton et al. 1986; Traynor et al. 1987). Differences have also been found in the amounts of pollution emitted by airtight vs. non-airtight stoves (Traynor et al. 1987). Hence, depending on the type of woodburning stove, its use in the home may introduce a significant amount of air pollution.

During the winter months, young children (especially preschoolers) tend to be confined within their homes for a great part of the day and definitely at night. Consequently, these children constitute a group which is maximally exposed to the indoor environment. Those children from homes with high levels of indoor air pollution during the winter months would be more likely to manifest outcomes of exposure, including acute chest illness.

The difference in the occurrence of chest illness in the present samples was both statistically and clinically significant. While outcome measures reported in this study were not season-specific, the results are consistent with findings previously reported by the authors on the occurrence of chronic symptoms of respiratory illness during the winter of 1982, where in the study group 77% and 84% had moderate and severe symptoms, respectively, as compared with 29% and 3% in the control group (Honicky et al. 1985; Osborne 1985; Osborne and Honicky 1986). If exposure to a woodburning stove is associated with the occurrence of acute chest illness and chronic respiratory symptoms, as these findings suggest, then it remains to determine which aspect(s) of woodburning stove use may be involved.

It is possible that respiratory illness in young children living in wood-heated homes may be associated with indoor air pollution from the combustion of wood. If this is correct, a reasonable mechanism could be pollutant-induced compromise of the ciliary action of ciliated epithelial cells, which are a significant component of the immune system throughout the tracheobronchial tree (Baum 1974; Fraser et al. 1988; Fishman 1988). Pollutant emission by-products of wood combustion that have been reported for woodburning stoves include carbon monoxide, nitrogen dioxide, sulfur dioxide, respirable particulates, aldehydes (such as acrolein), polycyclic organic compounds, benzo(alpha)pyrene, elemental

carbon, and a variety of priority pollutants and elements found in priority pollutants (e.g., aluminum, calcium, potassium, sodium, sulfur, and silicon) (Cooper 1980; Cooper and Malek 1982; Moschandreas 1980; Sexton et al. 1986; Traynor et al. 1987).

If any of these by-products of wood combustion are linked with illness occurrence, then the questions arise whether illness might be associated with a number of other factors related to heating with wood, including peak vs. average exposure, type of stove and location within the home, type and amount of wood burned, degree of airtightness of the home, and the temperature and relative humidity of the home. Peak exposure would occur during periods of maximum daily use and when the stove door is opened to add wood, while average exposure involves a time-weighted averaging of air exchange between the stove unit and the indoor environment. Although present data do not support an association between stove location or type of stove and the occurrence of chest illness, it may be that these factors have some effect, as might the type(s) and amount of wood burned. The air envelope around the house, the volume and degree of airtightness of the house, and the reintroduction of outdoor pollution from woodburning stoves to the indoor environment may also affect indoor air quality.

Another pertinent variable may be fluctuations in temperature in wood-heated homes as compared with homes heated by conventional means, which usually have a thermostat keeping indoor temperatures in a fairly narrow range. The relative humidity in the home may be another important factor, especially at night when woodburning stove use (which reduces indoor humidity) is greatest for indoor heating. The potential impact of these factors has not been determined but some are clearly candidates for affecting the occurrence of respiratory health outcomes.

In conclusion, the findings of this study indicated that young children living in homes heated by a woodburning stove were more likely to develop chest illness than children of the same age and sex who did not live in homes heated with a woodburning stove. Differences in the occurrence of chest illness were not accounted for by medical histories, frequency of physician visits, sociodemographic factors, or exposure to other sources of indoor air pollution investigated in this study and suggest that indoor heating with a woodburning stove may be a risk factor for chest illness in young children.

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DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: Your tests were accomplished in an area where heat is really required. Do you feel the same results would be found in areas where humidity is quite high and electric heat is the prime element for heating?

J.S. Osborne III, Kalamazoo Center for Medical Studies, Kalamazoo, MI: Duration and intensity of exposure are probably important factors with respect to health outcomes in young children. However, about 25% of the children whose homes were heated with wood in our study used a woodburning stove as a supplemental heat source (rather than primary) and they too manifested increased occurrence of chest illness. We believe relative humidity in the home is an important factor and, in areas of higher outdoor humidity, it would be reasonable to expect this to somewhat offset the reduction of indoor humidity from use of a wood-burning stove, depending on the volume and degree of airtightness of the home.

Marian L. Heyman, Hartford Steam Boiler Inspection and Insurance Co., Hartford, CT: Since a number of homes employed humidification systems, was consideration given to the possibility of contaminated humidifiers and/or humidification system components with microorganisms as factors in respiratory illness in children?

Osborne: Forty-eight percent of the homes in each group used at least one humidifier regularly. This is not surprising given the ages of the children in the study, the duration of Michigan winters, and the low indoor humidity during the heating season. It is reasonable to assume that humidifiers served as a mechanism of transmission for microorganisms and that this is reflected in the control group as well as the study group. The mechanism(s) whereby exposure to a woodburning stove may affect respiratory illness have not yet been determined, though it would be reasonable to speculate that pollutant-related compromise of the ciliated epithelial cells of the respiratory tract might alter susceptibility to infection from any source. However, the comparable distribution of humidifiers in the two groups suggests their use did not account for observed differences in the occurrence of chest illness.

THE EFFECTS OF ENVIRONMENTAL TOBACCO SMOKE ON ACUTE RESPIRATORY CONDITIONS

Bart David Ostro

ABSTRACT

Five years of the annual Health Interview Survey (HIS), conducted by the National Center for Health Statistics, are used to estimate the effects of air pollution, smoking, and environmental tobacco smoke on respiratory restrictions in activity for adults and bed disability for children. After adjusting for several socioeconomic factors, the multiple regression estimates indicate that an independent and statistically significant association exists between these three forms of air pollution and respiratory morbidity. The comparative risks of these exposures are computed and the plausibility of the relative risks is examined by comparing the equivalent doses with other studies that have used actual measurements of exposure taken in the homes of smokers. The results indicate that: (1) smokers will have a 55% to 75% excess in days with respiratory conditions severe enough to cause reductions in normal activity; (2) a one microgram (μg) increase in fine particulate matter air pollution is associated with a 3% excess in acute respiratory disease; and (3) a pack-a-day smoker will increase respiratory-restricted days for a nonsmoking spouse by 20% and increase the number of bed disability days for young children living in the household by 20%. The results also indicate that the estimates of the effects of environmental tobacco smoke on children are improved when the mother's work status is known and incorporated into the exposure estimate.

INTRODUCTION

Over the last three decades, researchers have been assessing the risks to the public health from cigarette smoking and air pollution. There is now considerable agreement that cigarettes and certain outdoor air pollutants adversely affect public health (U.S. DHHS 1984; National Research Council 1985). Cigarette smoke also significantly contributes to indoor air pollution levels, including potentially harmful gases and particulates. Nonsmokers, including both adults and children, exposed to environmental tobacco smoke may experience eye irritation, changes in pulmonary function, and increases in respiratory symptoms (U.S. DHHS 1986). There are few data sources containing health effects information that provide detailed individual-level estimates of smoking status, as well as exposure to both air pollution and environmental tobacco smoke. Epidemiologic research, designed to assess the risks from any one of these irritants, can be criticized because of the failure to control for other omitted exposures that may confound the estimates of risk. This paper addresses these shortcomings by empirically estimating the separate and concurrent risks from exposure to outdoor air pollution, environmental tobacco smoke, and mainstream smoke.

MATERIALS AND METHODS

To estimate the effects of smoking and air pollution on health, data from the Health Interview Survey (HIS), an annual survey conducted by the Census Bureau for the National Center for Health Statistics were used. It is a national, multistage probability survey of 50,000 households. Information on smoking habits was collected from a random one-third of the approximately 130,000 individuals in the survey. This analysis combined data from the 1976 through 1980 HIS and was limited to those households where at least two adults were sampled in the supplemental smoking questionnaire. With this information, the effects of smoking on one's nonsmoking spouse and the effects of parental smoking on children can be examined. The sample is drawn from metropolitan areas of all sizes and regions throughout the United States that are in the HIS and for which fine particulate matter air pollution measurements could be developed. From this remaining sample of roughly 7000 individuals, variables were constructed to estimate direct tobacco consumption and exposure to household tobacco smoke.

The multiple regression model and specification used in this analysis are similar to those used in Ostro (1987) and Hausman et al. (1984). Two groups are used in the analysis: adults, age 18 to 65, and children less than 6 years of age. Depending on the sample, different indicators of morbidity were used, based on the standard HIS two-week recall period. For adults, morbidity was indicated by the number of days of respiratory-related restricted activity in the two weeks prior to the day of the survey. Days of restricted activity, defined as any days where a respondent was forced to alter his or her normal activity, is a general indicator of health status. It includes days of work lost or bed disability as well as more minor restrictions. Respiratory conditions were determined from diagnoses reported in the HIS. For children, disability days spent in bed were used as the indicator of acute morbidity. While neither of these health outcomes are strict measures of respiratory impairment, any inclusion of nonrespiratory symptoms in the dependent variable will not bias the estimated regression coefficients. A dependent variable measured with an error that is unrelated to the independent variable will still produce slope coefficients that are unbiased and consistent (Pindyck and Rubinfeld 1976).

A Poisson distribution is used to model the event counts over time (i.e., the number of days ill) because of the large number of zeros (75% to 95%) in the dependent variables. Hausman et al. (1984) provide details on the efficiency and sensitivity of the Poisson assumption and a test, which indicated no misspecification, of the appropriateness of the model. The likelihood that N_{ijt} days of morbidity will occur in city i for individual j in the two-week time period t is described by (omitting subscripts):

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$$F(N) = e^{-Z} \cdot Z^N/N!$$

The expected value of N, which is Z, is allowed to vary among individuals according to the specification:

$$Z = exp\ (X \cdot b)$$

where X and b are vectors of explanatory variables and estimated parameters, respectively. The estimates of b are obtained by a maximum likelihood procedure.

Within each metropolitan area, different individuals were surveyed throughout the year. Their health survey response was merged with the two-week average of daily readings of outdoor particulate matter, a general indicator of ambient air pollution. Since current evidence (U.S. EPA 1982) implicates small particles rather than total suspended particles in causing health problems because of their potential to penetrate deep into the lung, estimates for fine particles (i.e., those less than 2.5 microns) were developed and used for this study. Based on regression equations developed by Trijonis (1982, 1983) fine particle concentrations were estimated using airport visibility data (see Ostro [1987] for details). Only airports within 9 km of the city center were used and all observations were corrected for humidity. This pollutant serves as an indicator for all pollutants resulting from fossil fuel combustion. The fine particulate concentration can be compared with the significant dose of particles (or tars) produced by cigarette smoking. Ostro (1985) has demonstrated that the relationship between fine particles and respiratory conditions is not affected by the inclusion of ozone or other pollutants.

Besides the air pollution variable, similar independent variables were included in each of the regression equations. These included age, sex, race, education (years of schooling), family income, quarter of the year in which the individual was surveyed, marital status, whether the individual was a current or former smoker, the existence of a chronic health condition, the maximum summer temperature and minimum winter temperature during the two-week recall period, and population density. When a subsample of only those currently working was analyzed, variables were added to control for paid sick leave (average number of days of sick leave disaggregated by industry group) and for occupation (white or blue collar).

Several different forms of the smoking variable were used to capture the effects of either direct or passive smoking. For direct effects, a binary variable was created to indicate whether any individual responded positively to the question, "Do you currently smoke?" There also was a measure of the number of cigarettes currently smoked every day. In each of the regressions for adults, a binary variable was included indicating whether the individual was a current or former cigarette smoker. For the measures of passive smoke exposure, different indicators were investigated. For adults, the alternative measures did not affect the general results, so the sum of the number of cigarettes smoked per day by all household members was used. For children, additional variables that detail the smoking and work status of the parents were considered in order to indicate the exposure to passive smoke.

Estimates of household smoking obviously are only an approximation of the real dose of tobacco smoke in the home and include a number of simplifications. First, the estimates assume that the number of cigarettes smoked during the day is independent of whether one is at work or not. Second, they do not differentiate between different types of cigarettes, the proximity and duration of the exposure to smoke, or ventilation rates in the home. Finally, the variables do not incorporate exposure to tobacco smoke at the workplace. This last shortcoming is mitigated by considering subsamples of the group, such as nonworkers. Thus, although the measures of passive smoke are crude, they do provide some index of the expected level of exposure to tobacco smoke.

TABLE 1

Correlation Coefficients for Sample of Current Workers

	Air Pollution	Current Smoker	Former Smoker
Age	−.02	−.06	.17
Education	−.04	−.14	.05
Income	−.03	−.11	.09
Married	−.01	−.07	.13
1st Quarter	−.07	.01	−.00
2nd Quarter	.01	.00	−.00
3rd Quarter	.16	−.03	.03
Density	−.17	.01	−.01
Winter Min Temp	−.03	.00	−.02
Summer Max Temp	.16	−.02	.02
Nonwhite	.07	.02	−.07
Chronic condition	.03	.01	.06
Air Pollution*	1.00	.01	−.00

Note:
* = measured as fine particulate matter

The existence of an omitted or confounding variable is always possible in an observational study. However, for an omitted variable to affect the results of this analysis, it must be related to both the explanatory variables of interest—air pollution, smoking status, and passive smoke—and the dependent variable. The inclusion of various socio-economic measures such as income, race, sex, education, and occupation will reduce the possibility of any omitted variable bias. In addition, as indicated in Table 1, the potential for confounding is low, since the correlations among the explanatory variables were low. The variables with the highest correlation with particulate matter air pollution were summer maximum temperature ($r = .16$), population density ($r = -.17$), and being surveyed in the third quarter (.16). Current smoking had the highest correlation with education ($-.14$) and income ($-.11$), while being a former smoker was correlated with age (.17), being married (.13), being male (.20), and income (.09). None of these correlations appears large enough to significantly confound the relationships between air pollution, smoking, and health. The problem was minimized further by considering successively smaller and more homogeneous subsamples of the adult population. Thus, results for the following subsets are reported:

1. All workers
2. All nonsmokers
3. All never-smoking nonworkers
4. Female, never-smoking nonworkers

First, the entire sample of those currently working, aged 18 to 65 ($n = 3634$) was used. This group has fairly similar activity patterns but, since it includes both smokers and nonsmokers, the effects of direct vs. passive smoke may be difficult to separate. Therefore, a sample consisting only of nonsmokers was analyzed next. Finally, to eliminate the in-

TABLE 2

Estimated Regression Coefficients for Respiratory-Related Restrictions in Activity, Workers, Age 18–65 (n = 3634) (standard errors in parentheses)

Variable	Mean	(Model 1)	(Model 2)	(Model 3)
FP	23.2	3.13 (0.26)	3.23 (0.27)	3.21 (0.27)
FOSMO	0.22	70.0 (11.0)	69.9 (11.6)	21.7 (8.6)
COSMO	0.41	74.1 (9.56)	55.5 (10.8)	
TOTCIG	17.17		0.83 (0.16)	
RRAD	2.5			

Note: FP = Two week average of fine particulate air pollution, lagged two two-week periods (micrograms per cubic meter).
FOSMO = Binary variable indicating former smoker (0, 1).
COSMO = Binary variable indicating current smoker (0, 1).
TOTCIG = Total number of cigarettes smoked by household members.
RRAD = Days of respiratory-related restrictions in activity per year.

All coefficients are significant, using two-tailed test, at $p < .01$. Coefficients are $\times 100$ and are interpreted as percent change in respiratory conditions due to a one unit change in the independent variable.

The other independent variables included in each regression (with their means) include:

Age (38.14), Race (17.6% nonwhite), Sex (40% female), Education (12.6 years), Family income ($22,046), Quarter of the year of survey (first 21.3%, second 23.4%, third quarter 27.6%), Marital status (65.6% married), Occupation (32.3% blue collar), Existence of chronic condition (6.5%), Minimum winter temperature (23.3), Maximum summer temperature (87.4), Paid sick leave (4.32 days), and Population density (7722 per square mile).

fluence of current exposure to occupational irritants, subsamples of never-smoking nonworkers were considered.

RESULTS

Table 2 presents the estimated coefficients for the smoking and air pollution variables for the regressions using the full sample of those currently working. The results of Model 1 (column 1) indicate a positive association between being either a former or current smoker and the number of days with a respiratory condition. In addition, the results indicate that exposure to fine particulate matter will affect respiratory health. In Model 2, a variable measuring the total number of cigarettes smoked daily by household members was added to the regression to incorporate the impact of environmental tobacco smoke. In Model 3, the effect of the omission of any of the smoking variables on the air pollution variable was measured. Specifically, the results indicate that the regression results are not affected by the omission of either direct or passive smoking; the coefficient for fine particulate air pollution remains unchanged from the specifications of Models 1 through 3.

To eliminate the problem of collinearity in the regressions between the measures for current smoking and for passive smoking (i.e., total number of cigarettes smoked by the household), a sample of currently nonsmoking adults was considered. The results of the multiple regression Model 4, shown in Table 3, again indicate that the air pollution and passive smoke variables are each significantly related to respiratory-related restrictions in activity.

Next, to better isolate the effects of passive smoke, former smokers were eliminated from the sample and a subsample consisting only of never-smokers, not currently working ($n = 979$), was considered. This sample is not exposed to occupational irritants and does not, by definition, include either current or former smokers. As displayed in Table 3, Model 5, the measures of air pollution and passive smoke each have a statistically significant relationship with respiratory illness.

In the final regression for adults, in Model 6, a sample of nonworking, never-smoking females ($n = 782$) was considered. Again, both air pollution and passive smoke are significantly related to restricted activity days. These last two subsamples produce the most convincing evidence about the ill effects of passive smoke in that the groups are not currently being exposed on the job and are not current or former smokers.

The results of the analysis of the effects of secondhand smoking on the number of disability days spent in bed by children age zero to six years are displayed in Table 4. To represent the effects of passive smoking, the same measure used above, the total number of cigarettes smoked by household members, was used. A number of refinements to this measure also were considered and are detailed below. The rest of the independent variables in the regression equation were similar to those used for the adults and include: age, sex, education of head of household, family income, national origin (Asian, Hispanic, Black), the existence of a chronic disease, family size, the quarter of the year of the survey interview, winter minimum and summer maximum temper-

TABLE 3

Estimated Regression Coefficients for Respiratory Related Restrictions in Activity, Age 18–65 (standard error in parentheses)

	All Nonsmokers (n = 3801)		Nonworking Never Smokers All (n = 979)		Nonworking Never Smokers Female (n = 782)	
Variable	(Model 4) Mean		(Model 5) Mean		(Model 6) Mean	
FP	23.54	1.35 (0.17)	24.14	1.07 (0.37)	24.33	1.38 (0.37)
FOSMO	0.34	71.6 (5.44)	—		—	
COSMO	—		—		—	
TOTCIG	8.26	0.85 (0.18)	8.3	0.94 (0.41)	8.5	1.14 (0.42)
RRAD	3.58		4.73		5.55	

Note: FP = Two week average of fine particulate air pollution, lagged two two-week periods (micrograms per cubic meter).
FOSMO = Binary variable indicating former smoker (0, 1).
COSMO = Binary variable indicating current smoker (0, 1).
TOTCIG = Total number of cigarettes smoke daily by household members.
RRAD = Days of respiratory-related restrictions in activity per year.

All coefficients are significant, using two-tailed test, at $p < .01$. Coefficients are $\times 100$ and are interpreted as percent change in respiratory conditions due to a one unit change in the independent variable.

The other independent variables included in each regression (with the means for model 4) include:

Age (39.13), Race (16.7% nonwhite), Sex (45% female), Education (12.7 years), Family income ($20,796), Quarter of year of survey (first 14.4%; second 24.6%; third 31.1%), Marital status (66.7%) Work status (64.5% working), Existence of chronic condition (12.8%), Minimum Winter Temperature (25.4), Maximum Summer Temperature (87.0), and Population Density (8245 per square mile).

TABLE 4

Estimated Regression Coefficient for Bed Days, Children Age 0–6 (n = 1575) (standard error in parentheses)

Variable	Mean	(Model 7)	(Model 8)	(Model 9)	(Model 10)
FP	23.86	0.88* (0.30)	0.86* (0.31)	0.87* (0.30)	0.86* (0.30)
TOTCIG	16.79	0.37* (0.14)			
DADCIG	9.76		−0.22 (0.14)		
MOMCIG	7.03		0.21# (0.11)		
MOMSMHO	0.23			18.7* (6.1)	
MOMCIGHO	4.24				0.76* (0.28)
BEDDAYS	6.28				

Note: FP = Two week average of fine particulate air pollution, lagged two two-week periods (micrograms per cubic meter).
TOTCIG = Total number of cigarettes smoked daily by household members.
DADCIG = Cigarettes smoked daily by male adult in household.
MOMCIG = Cigarettes smoked daily by female adult in household.
MOMSMHO = Binary variable indicating presence of a nonworking, smoking, female adult in the household.
MOMCIGHO = Number of cigarettes smoked daily by nonworking female adult in the household.
BEDDAYS = Bed disability days per year.

* = significant at $p < 0.01$, two-tailed test
# = significant at $p < 0.10$, two-tailed test

Coefficients are ×100 and are interpreted as percent change in respiratory conditions due to a one unit change in the independent variable.

The other independent variables included in each regression (with their means) include:

Age (3.06), Race (74% white; 16% black; 8% Spanish; 2% Asian), sex (48% male), Education of head of household (12.65 years), Family income ($17,770), Quarter of year of survey (1st: 18%; 2nd: 28%; 3rd: 26%), Existence of chronic condition (2%) Minimum winter temperature (23.8), Maximum summer temperature (92.5) and Population density (8,316).

atures, and air pollution (measured in terms of fine particulate matter).

The results indicate a generally positive and significant relationship between the passive smoke measure and the number of days spent in bed for children. In Model 7, for example, coefficients for air pollution and the total number of cigarettes smoked daily by household members are both positive and significantly related to bed disability days. This estimated effect is significant since the HIS data indicate that 62.3% of the children have at least one parent who smokes, while 7.3% have two parents who smoke.

In regression Model 8, variables were included indicating the number of cigarettes smoked separately by the male and female adult at the home. As may be expected, only the adult females' smoking status had a positive association with child illness. The coefficient for the male adult was not different from zero. With this indication that the female adult's smoking status was a better indicator of a child's exposure to secondhand smoke, in Model 9 a binary variable was included that took on a value of one if the female adult in the household was a smoker and also currently not working. This greater detail in the exposure measure increases the efficiency of the estimate. Specifically, the regression indicates that children with a smoking, nonworking female adult in the home will have 18.7% more bed days than children with "other" (either smoking and working, or nonsmoking) female adults. Finally, Model 10 considers the number of cigarettes smoked by the nonworking, smoking female adults. Overall, these estimated effects are important since the HIS data indicate that 20% of the children in this age bracket live with a nonworking female adult who smokes.

The impact of acute illness of the parents was also tested. A binary variable was created that indicated whether either the adult male or female living in the household had a respiratory-related restriction in activity during the two-week recall period. While parental respiratory illness was significantly associated with the child's bed days, the estimated coefficient of the passive smoking variable was not affected by the inclusion of this variable.

DISCUSSION

The results of the above analysis indicate that all three sources of "air pollution"—outdoor ambient air pollution, direct consumption of cigarettes, and environmental tobacco smoke—are statistically associated with respiratory-related restrictions in the activity of adults. There is also an indication that air pollution and passive smoke are associated with an increase in illness in children, measured as the number of days spent in bed for health reasons.

From the empirical evidence, an exposure-response relationship was estimated for all three sources of air pollution. Also, concerns about the potential confounding between the effects of smoking and outdoor air pollution on health were addressed. Therefore, the comparative risks from the three different air pollutants and the equivalent doses can be determined.

In interpreting these results, one must be particularly aware of selection bias problems. For example, some people will select themselves out of the labor market or out of tobacco consumption because of health conditions. It is possible, therefore, that for some subgroups, the current smokers may appear healthier than former smokers, since the latter may have either quit because of respiratory problems or, in extreme cases, may have died. There is also a possibility of reporting bias regarding smoking status; specifically, that smokers may not admit to currently smoking. However, this would bias the air pollution estimate only if smokers in either high *or* low air pollution cities consistently tended to misrepresent their status. In addition, if a current or former smoker is misrepresented as a "never" smoker, this would tend to underestimate the effects of smoking.

The Poisson regression results for adults indicate that the estimated relationship between outdoor air pollution, measured as fine particulate matter, and days with respiratory-related restrictions in activity, is not affected by the exclusion or inclusion of any of the smoking variables (see Tables 2 and 3). The persistence of the effect, regardless of the specification of the smoking status, may be due to the relatively low correlation between smoking and air pollution. A lag of two two-week periods prior to the survey recall period (i.e., the third and fourth weeks before the two-week recall period) provided the best fit between air pollution and health.

The sample consisting of current workers (Models 1 through 3) may comprise the best sample for determining the risk of fine particulate air pollution since their normal activity patterns are relatively similar and restrictions in their activity are easier to note. The results indicate that a one μg per m^3 change in fine particles results in a 3.2% excess in acute respiratory disease, or an annual increase of 8000 days of respiratory-related restrictions per 100,000 (3.2% change in

TABLE 5

Effects of Smoking on Acute Respiratory Symptoms

Author, reference	Effect	Percent Increase in Prevalence for Smokers
Bland et al.[a] (1978)	Morning cough, boys	29
	Morning cough, girls	233
	Cough at other times, boys	70
	Cough at other times, girls	84
	Breathlessness, boys	82
	Breathlessness, girls	71
Bouhuys et al.[b] (1981)	Cough, men	195
	Cough, women	98
Burghard et al. (1979)	Morning cough	88
	Day or night cough	72
Dean et al.[c] (1978)	Phlegm, men	136
	Phlegm, women	244
Gulsvik (1979)	Morning cough	227
	Daytime cough	300
	Phlegm when coughing	180
Park (1981)	Morning cough	113
	Daytime cough	160
	Nightime cough	47
	Morning phlegm	30
	Daytime phlegm	−43
	Nightime phlegm	80
	Breathlessness on exertion	28
Neukirch et al. (1982)	Cough and/or phlegm, boys	34
	Cough and/or phlegm, girls	66
Kristein (1983)	Work loss days	33–45

Notes:
a = comparing nonsmoker to occasional smoker
b = uses average for all cities
c = assumes 20 cigarettes consumed by smoker

respiratory illness/μg per m^3 x 2.5 mean annual days of respiratory illness x 10^5). For children (Table 4), a 1 μg increase in fine particles results in an increase of 0.86% days in bed, or an annual increase of 5400 days per 100,000 (0.86% x 6.28 mean annual bed days x 10^5). The sample of individuals currently working also was used to estimate the direct effect of smoking. Table 2 indicates that relative to never-smokers, this group has a 55% to 75% excess in days with respiratory conditions severe enough to cause reductions in normal activity. By definition, this estimate compares two groups that are similar except for smoking status, and controls for several socioeconomic factors including age, race, sex, income, education, occupation, and number of days with sick leave. This range is similar to that reported in other studies of acute respiratory symptoms. While smokers have two to four times more chronic respiratory disease (U.S. DHHS 1984), existing research indicates that they have 20% to 80% more acute respiratory symptoms (see Table 5 for a summary of these studies). Thus, the estimates predicted from this analysis are within the range provided by the earlier studies.

This analysis also indicates that former smokers may continue to have up to 70% more respiratory-restricted activity days (or 2.5 days per person) than the population of never-smokers. This large effect may be a result of the smoking cessation by those with existing chronic disease.

The best estimate of the impact of secondhand smoke is obtained from the sample of nonsmokers or of never-smoking nonworkers. For the latter group there is no confounding from direct smoking or from acute occupational exposure. As indicated by Model 5 (Table 3), for example, there may be almost a 1% increase in acute respiratory illness per cigarette smoked per day by household members. This amounts to 0.062 days per year per cigarette (i.e., estimated coefficient indicating 0.94% increase in respiratory illness days per cigarette x mean annual days of respiratory illness for this group of 6.6). The results also indicate that the exposure estimate was not improved by weighting the amount smoked by an individual by a national average of the expected time spent at home for a given sex and work status.

The estimated acute effect of environmental tobacco smoke is larger relative to the impact of smoking (i.e., from Table 2, 0.83% per passive cigarette vs. 75% per pack, or 3.75% per direct cigarette) than existing estimates of exposure would suggest. For example, the National Research Council (1981) estimated that the average particulate matter "dose" from passive smoke is about 1% of the direct dose from smoking. The larger-than-proportional impact on health from environmental tobacco smoke indicated by this analysis may be due to several factors including: the smoking spouse being visited at the home by other smokers; the nonsmoking spouse frequently being close to the plume generated by the smoker (the NRC estimate was based on average ambient levels in a public place or in the smoker's home); differences by smoking status in particle retention and clearance efficiency; and differences in constituents between mainstream and sidestream smoke. Further research is indicated regarding the effective dose from sidestream vs. mainstream smoke.

Regarding children, the results indicate that a child with a nonworking, smoking female adult in the home will have almost one more day per year (a 19% increase) spent in bed for health reasons than would other children. These numbers are consistent with Ware et al. (1984) who suggested a 20% to 35% increase in the risk of all respiratory illnesses and symptoms due to maternal smoking; Bland et al. (1978) (16% increase in day or night cough); Schenker et al. (1983) (18% increase in chest illness before age two and 34% increase in the prevalence of more than three days of chest illness); Cameron et al. (1969) (33% increase in rates of respiratory illness with restricted activity); and Bonham and Wilson (1981) (6% increase in restricted activity days for children under six). The latter paper was based on the 1970 HIS and used analysis of variance and comparisons of the means to indicate that children in families that smoked more tended to have more bed-disability days and restricted activity days. However, Bonham and Wilson (1981) did not provide quantitative estimates of risk and only controlled for a few of the potentially confounding influences on the children.

The results for children indicate that the exposure estimate is dramatically improved when maternal smoking habits are used in the model. These findings are consistent with those reported by Tager et al. (1983), Weiss et al. (1980), and Ware et al. (1984), and are probably a result of the greater amount of time children spend with their mothers. Further improvements in the estimates occur when the mother's work status is known and incorporated into the exposure estimate.

Besides comparing these results with those obtained from previous research, one can check the plausibility of the results by computing the equivalent dose (in μg per m^3 of respirable particulates) of secondhand smoke relative to ambient par-

ticulate matter. Although there are many different measures that can be used to classify the nonsmokers' exposure to tobacco smoke, total respirable particulates may be the best measure of the potential risk for acute respiratory conditions.

Thus, to test the plausibility of the passive smoke results, fine particles (FP) were first converted to respirable particles (RSP) (i.e., particles roughly below 10 microns) using the ratio FP/RSP = 0.95 reported by Sexton (1984). Using the results derived earlier indicating a 1 μg increase in fine particles relates to an increase of 0.08 days with respiratory restrictions, 1 μg of respirable particulates relates to 0.08 restricted days. Since it also has been determined (Model 6) that one passive cigarette relates to 0.062 restricted days, this implies that one passive cigarette has the same impact as 0.79 (i.e., 0.062/0.084) μg of respirable particulates. Stated differently, a pack-a-day smoker would generate the equivalent health impact of 14.8 μg per m^3 of respirable particulates. Dockery and Spengler (1981a, b) have empirically determined from actual exposure measurements that in the average house, a pack-a-day smoker contributes 18 μg per m^3 of respirable particles. Other equivalent doses could be calculated using other subsamples. Regardless of the specific sample used, however, the estimates appear plausible when compared with the observed pack-a-day exposure of 18 μg.

CONCLUSIONS

In sum, evidence from the Health Interview Survey indicates a consistent statistical association between respiratory conditions and exposures from air pollution, smoking, and passive smoke. The results indicate that: (1) smokers will have a 55% to 75% excess in days with respiratory conditions severe enough to cause reductions in normal activity, (2) a 1 microgram increase in fine particulate matter air pollution is associated with a 3% excess in acute respiratory disease, and (3) a pack-a-day smoker will increase respiratory restricted days for a nonsmoking spouse by 20% and increase the number of bed disability days for young children living in the household by 20%. The results also indicate that the estimates of the effects of environmental tobacco smoke on children are improved when the mother's work status is known and incorporated into the exposure estimate.

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DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: Did you take into consideration teenagers or other smokers in a home? If not, why? That could play a very important part in your continued study.

B.D. Ostro, California Public Health Foundation, Berkeley, CA: No, teenagers were not included since their activity patterns, specifically the amount of time and time of day they spend at home, is so variable. Obviously, they would contribute to the overall dose of ETS.

Behzad Samimi, Graduate School of Public Health, San Diego State University, San Diego, CA: You stated in your presentation about assessment of visibility for submicroscopic particles. I wonder what technique you used for this assessment? Did you measure the visibility in terms of COH (coefficient of haze)? Did you use a tape sampler for this purpose? What technique was used to assess and characterize the fine particles? Since less than 10 μm particulate were measured, what type of size selector did you employ?

Ostro: Airports are required to report visibility every hour, based on visual markings, not direct ambient measurements. Equations involving atmospheric chemistry have been developed that relate the inverse of visibility to fine particles (less than 2.5 microns) after correcting for humidity and other meteorologic factors.

Air Purification and Humidity

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AIR CLEANERS FOR VOLATILE ORGANIC COMPOUNDS IN INDOOR AIR

K. Ramanathan M.K. Owen V.L. Debler M.A. Kosusko L.E. Sparks

ABSTRACT

The feasibility of activated carbon adsorption for the control of volatile organic compound (VOC) emissions at indoor air concentration levels (ppb) was investigated. Adsorption data for VOC at concentrations below 10 ppm are not publicly available. Adsorption isotherms for benzene, acetaldehyde, and 1,1,1-trichloroethane in the 100- to 200-ppb range were obtained on three different carbons using a microbalance. Two different models were used to predict in-duct carbon filter lifetimes based on the experimental data. The results show that the small quantities of carbon used in panel and duct filters appear to have limited usefulness in indoor VOC control.

INTRODUCTION

Indoor air environments, where humans spend the majority of their time, can contain significant levels of volatile organic compounds (VOC). Because many of these compounds are potentially toxic, it is necessary to determine ways to control these compounds through source removal and heating, ventilating, and air-conditioning (HVAC) system modification, including the incorporation of air cleaners. This paper presents the results of a study to determine the feasibility of carbon adsorption for the control of VOC in indoor air.

BACKGROUND

Sources

There is a wide variety of sources of VOC in indoor air. These sources vary tremendously depending on the nature of the facility, but often include contributions from outdoor air that enters the building through leaks and through the HVAC system. Other typical sources include combustion, smoking, building materials, and office machines. Various studies of indoor air quality (IAQ) have identified more than 250 organics at levels greater than 1 ppb (Sterling 1985) with concentrations expected in the few hundred ppb range but not exceeding a few ppm (Wallace et al. 1987; Wang 1975; Tucker 1986).

Controls

In evaluating the feasibility of different control strategies, a maximum allowable level for each pollutant is needed. Unfortunately, toxicity data are lacking for many of the compounds. Therefore, arbitrary criteria, such as odor, are often used. Depending on the compound, these may or may not be adequate from a health standard perspective.

Source removal and ventilation have received the most attention as control strategies. However, source removal is not always practical because, for example, offices need photocopy machines to be readily accessible. Also, increasing the ventilation rate can result in prohibitively high HVAC costs.

TABLE 1

Carbon Properties

Carbon/property	Coal base	Pinewood charcoal base	Coconut shell base
Activation method	Steam	Steam	Steam
CCl_4 Adsorption wt. % (min)	60	65	60
Surface area m^2/g	1,050–1,150	1,150	1,050–1,150

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Therefore, it is apparent that practical methods for the removal of organic vapors need to be developed. Adsorption, absorption, incineration, and catalytic conversion are removal techniques for pollutant gases. All have demonstrated applicability in conventional pollution control applications and could be incorporated into an HVAC system with minimal retrofit. However, adsorption on carbon seems to be the most popular technique currently in use for indoor applications. A review by Turk (1977) discusses this applicability in detail.

Two commercially available air-cleaning devices incorporating activated charcoal as the removal technique for VOC were studied by Daisey and Hodgson (1988). Two other devices were examined in the same study, but these used additional techniques (such as catalytic oxidation) to reduce the VOC level. The two carbon-only devices showed extremely low efficiencies (from 0% to approximately 6%) for VOC removal (which indicate low adsorption). Deitz (1988) also suggests that there may be problems with the use of activated carbon for gas and vapor removal in HVAC systems. These results show the need for additional research into the efficacy of carbon adsorption for indoor air VOC control. It is especially important to test the carbon by itself to determine, without question of interference, the potential of activated carbon for use in IAQ control devices.

PURPOSE OF THE STUDY

The majority of adsorption systems currently marketed for indoor air pollution applications deal with odor control. These systems consist primarily of in-duct carbon filters.* Quantifiable performance data are not available for any of the systems surveyed. The carbon in each unit is assumed to be spent when occupant complaints increase. Obviously, this method of bed lifetime estimation has drawbacks, particularly when dealing with potentially toxic compounds that have relatively high odor thresholds. Adsorption isotherm data in the

*More detailed information on the vendor survey can be obtained from the authors.

K. Ramanathan, M.K. Owen, and **V.L. Debler** are with the Research Triangle Institute, Research Triangle Park, NC. **M.A. Kosusko** and **L.E. Sparks** are with the Air and Energy Engineering Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC.

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TABLE 2

Summary of Adsorption Results

Compound	Uptake[a] ($\times 10^7$)		
Acetaldehyde	Wood-base	Coal-base	Coconut shell-base
Concentration (ppb)	mol CH_3CHO/g C	mol CH_3CHO/g C	mol CH_3CHO/g C
119	3.39	3.52	10.0
153	4.17	10.00	10.0
Benzene	Wood-base	Coal-base	Coconut shell-base
Concentration (ppb)	mol C_6H_6/g C	mol C_6H_6/g C	mol C_6H_6/g C
101	2.42	1.24	4.30
119	4.30	6.37	5.60
176	10.00	7.27	6.33
1, 1, 1-Trichloroethane	Wood-base	Coal-base	Coconut shell-base
Concentration (ppb)	mol CH_3CCl_3/g C	mol CH_3CCl_3/g C	mol CH_3CCl_3/g C
115	0.749	1.15	2.04
183	1.33	2.80	1.91

[a]Each number represents the average of 3 to 4 data points.

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low concentration regime (<10 ppm) are not publicly available, even for simple compounds, on any carbons. This led to our effort to obtain adsorption isotherms in the ppb range in order to determine the applicability of activated carbon adsorption for indoor air pollution control.

EXPERIMENTAL DESIGN

Three types of activated carbon were tested: a coal-based carbon, a wood-based carbon, and a coconut-shell-based carbon. Table 1 lists some of the physical characteristics of these carbons.

The pollutants chosen were relatively simple, low molecular weight compounds representative of three different classes of organic compounds: benzene (aromatic hydrocarbon), acetaldehyde (oxygenated hydrocarbon), and 1,1,1-trichloroethane (halogenated hydrocarbon). Isotherms were measured in the 100- to 200-ppb range for each compound. This concentration range was chosen based on measurements of VOC concentrations reported in the literature (Sterling 1985; Wallace et al. 1987; Wang 1975).

Materials and Equipment

The low concentrations were generated with clean, dry airstreams flowing over permeation tubes with certified permeation rates. These tubes had permeation rates of 71.3 ng/min for benzene, 148 ng/min for 1,1,1-trichloroethane, and 12.5 ng/min for acetaldehyde. Nitrogen was used as a purge gas during degasing. All gases used had purities greater than 99.999%.

The experimental setup is shown in Figure 1. It consisted of two mass flow controllers with flow ranges of 0 to 1000 cm³/min and 0 to 100 cm³/min, a microbalance, and a thermostatted water bath for the permeation tubes and balance jacket.

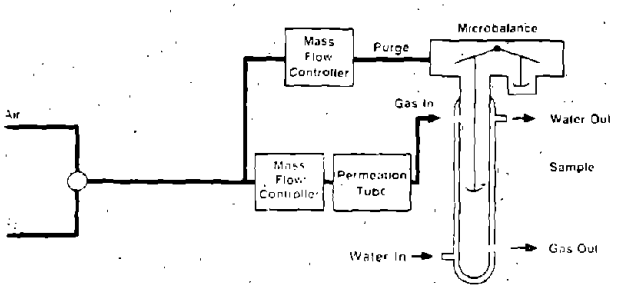

Figure 1 Schematic of experimental setup.

The microbalance was used for the adsorption studies. It is capable of weighing up to 100 g with an accuracy of ±0.5 μg. This device may be operated under low-temperature, high-vacuum conditions for the determination of BET surface area and is ideally suited to make adsorption isotherm measurements under different pressure and temperature conditions.

Experimental Procedure

Gravimetric measurement of adsorption isotherms can be carried out in either a static or dynamic mode. The static mode, usually under a vacuum, has the advantages of a high signal-to-noise ratio and a fairly good control of partial pressure of adsorbate. However, equilibration times can be very long, particularly at low concentrations, and the conditions are not representative of real systems, where air is present with the adsorbate and may affect its adsorptivity. The authors chose to operate in the dynamic (flow) mode, at atmospheric pressure, in order to reduce experimental time and measure adsorption under conditions more representative of streams challenging real-world filters.

The carbon sample (150 to 200 mg) was degased under flowing nitrogen while it was heated with an infrared lamp. Degasing was assumed to be complete when the weight remained constant for 10 to 15 minutes. The sample was then allowed to cool in nitrogen to 30°C before switching to the airstream and introducing the permeation tube. Although this temperature is high relative to HVAC applications, temperature control at lower temperatures was found to be very difficult. We do not believe that this will qualitatively affect the conclusions reached in this study. Flow rates were adjusted to give the desired concentrations. Equilibrium was assumed when the weight gain (on the 100-μg scale) leveled off (rate of weight gain < 4 μg/h).

RESULTS

It is no accident that there is a paucity of scientific data on the effectiveness of activated carbon for organic vapor removal at the ppb level. Experiments to measure uptakes, either through changes in gas-phase concentrations or gra-

vimetric techniques, are extremely laborious and can be very expensive. It is only very recently that concern about potential health effects at low concentration levels has begun to justify the effort and expense involved. While there are various reports about the capacity of carbons in use for controlling different emissions (Turk 1977), details about the composition and concentrations of the streams tested are often lacking.

It must be admitted, prior to discussion of the results, that there are many potential sources of error in the low concentration/low uptake experiments described in this study. Extreme care was taken to minimize errors in measurement. Replicate runs were used to confirm the values obtained. While there may be some question as to the absolute values of uptake measured, the authors believe that any error incurred was not significant enough to materially affect the conclusions of the study.

Table 2 summarizes the results for the uptakes of organic pollutants on the various carbons. It is apparent that the capacities (mol/g carbon) do not vary much with either compound or carbon in the concentration range studied. Capacities ranged from 10^{-8} to 10^{-6} mol/g. Acetaldehyde uptake is about two to three times higher than the other compounds studied. Figures 2, 3, and 4 represent the isotherms over the concentration ranges studied. The magnitude of isotherm slopes in the concentration range studied decreased from benzene to 1,1,1-trichloroethane to acetaldehyde. Higher isotherm slopes indicate more favorable adsorption. The data for benzene, for which three data points are available, were linearized in order to obtain an equation for use in a predictive packed bed model. Although the data (Figure 2) do not appear to fit a straight line through the origin very well, we hoped that this exercise would give us a feel for the applicability of carbon adsorption to indoor air pollution control. Table 3 lists the linearized isotherms for benzene adsorption on the three carbons in this study.

It is possible that, at the extremely low concentrations studied, chemisorption may be a major contributor to measured uptake. The fact that carbons used in indoor applications are generally very difficult to regenerate lends some support to this hypothesis. Significant chemisorptive effects may be the explanation for certain apparent anomalies in the observed results, such as lower uptakes for 1,1,1-trichloroethane than for acetaldehyde.

Isotherm data are useful for carbon screening and provide an upper bound on the capacity of the adsorbent, but they do not provide direct practical information on the applicability of the technique. For this reason, estimates of the carbon filter size were carried out using a method recommended by the manufacturer of two of the carbons and a model developed by RTI. This is a standard fixed-bed breakthrough model that makes the assumption of (1) a linear isotherm, (2) plug flow, and (3) no radial or axial dispersive effects (EPA 1987). Two methods were used in order to compare results. The superficial velocity of gas across the filter was assumed to be 12.7 cm/s, corresponding to a flow of 100 cfm (2830 lpm) across a 2 ft by 2 ft (61 cm by 61 cm) filter. An exit concentration of 50 ppb was set as the level corresponding to useful bed life.

The first method was applied to the data for all three compounds, with challenge concentrations varying from 115 to 183 ppb. The lifetime for 6-in-thick (15-cm-thick) filters, such as those typically marketed for odor control applications, was determined. The results in Table 4 show that breakthrough occurs rather quickly, bringing into question the applicability of a once-through filter even in the absence of other pollutants or humidity effects, both of which would cause performance to deteriorate further.

The second method, the RTI program, was applied to the benzene data because it probably represents the best case

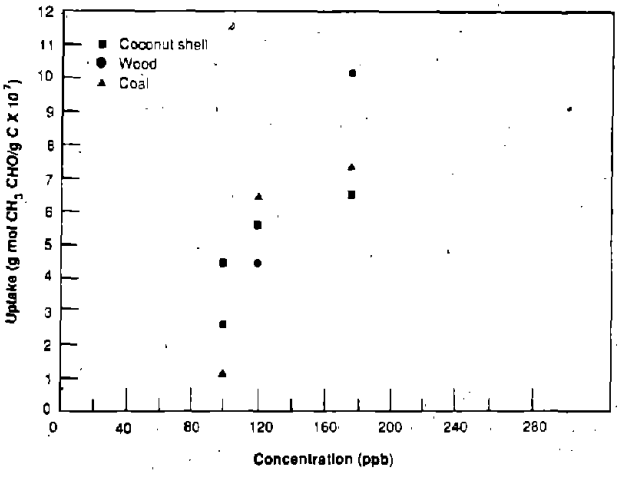

Figure 3 Adsorption of benzene on activated carbons

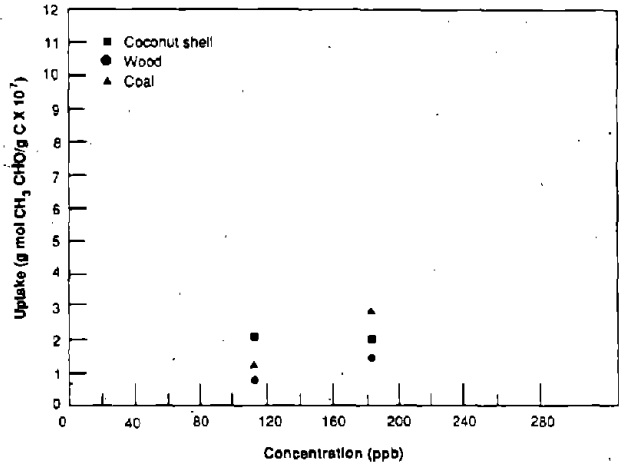

Figure 2 Adsorption of 1,1,1-trichloroethane on activated carbons

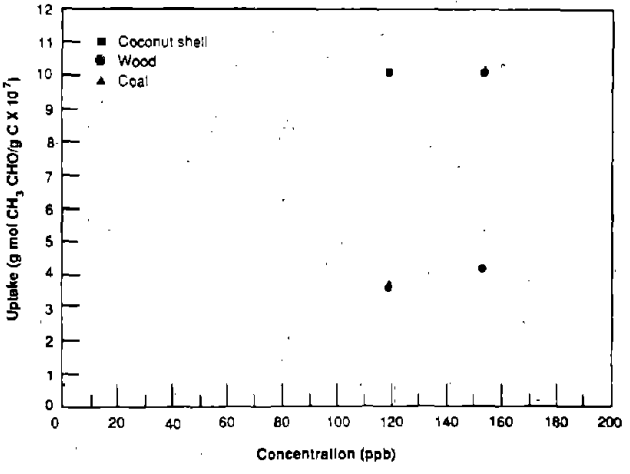

Figure 4 Adsorption of acetaldehyde on activated carbons

TABLE 3

Linear Equations for Benzene[a]

Carbon type	Uptake		
Wood-base	$1.0 \times 10^{-8}\ C_b$	-7.7×10^{-7}	mol C_6H_6/g C
Coal-base	$6.5 \times 10^{-9}\ C_b$	-3.6×10^{-7}	mol C_6H_6/g C
Coconut shell-base	$2.4 \times 10^{-8}\ C_b$	$+2.3 \times 10^{-7}$	mol C_6H_6/g C

[a] C_b = Benzene concentration in ppb

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TABLE 5

Variation of Exit Concentration with Bed Depth[a]

T = 4,320 h (6 mo)		T = 30 h	
L (ft)[b]	C exit (ppb)	L[b] (ft)	C exit (ppb)
1,098.64	121	7.65	114
1,097.67	115	8.15	55.6
1,108.95	99.5	8.31	35.1
1,137.29	67.2	8.41	20
1,163.09	40.6		

[a] 150 ppb benzene challenge
12.7 cm/s superficial velocity
3.0 mm particle size
Coconut-shell-based carbon

[b] 1 ft = 0.3048 m

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for the compounds studied. The linearized form of the equation on the coconut-shell-based carbon was used. The challenge concentration was assumed to be 150 ppb, and the other variables were set as before. Table 5 lists the results of this simulation. Again, breakthrough is shown to occur quickly.

This result reinforces the conclusion from the first method calculations that filter life would be extremely short, making these filters of negligible value as in-duct indoor air filters. However, it is important to note that the level at which acceptable breakthrough is set is critical to bed lifetime. In the absence of toxicological data, this may have to be set rather arbitrarily, erring on the side of caution.

The results of this study are also supported by the results reported by Daisey and Hodgson (1988). Both studies show that the small quantities of carbon used in panel and duct filters appear to have limited usefulness in controlling indoor air VOC at the extremely high face velocities often encountered. While it is true that most in-duct filters are used in multi-pass as opposed to once-through modes, these simulations represent the results for the first pass, where best performance would be expected. Carbon devices using more complex flow schemes (involving parallel beds with regeneration) may work, but they may be uneconomical except in very large-scale applications. Carbon adsorption may be viable in the event of major surges in concentration, such as spills or releases, which push the ambient concentrations into regimes where the shape of the isotherm is more favorable and sufficient driving force exists for a reasonable uptake.

TABLE 4

Calculated Lifetime of a 6-inch Carbon Bed

Gas	Mole fraction ($\times 10^{-7}$)	Lifetime (min) Wood	Coal	Coconut shell
Benzene	1.01	1.02	0.52	1.82
	1.19	1.54	2.29	2.01
	1.76	0.24	1.76	1.54
Acetaldehyde	1.19	1.22	1.26	7.14
	1.53	1.16	2.79	2.79
1, 1, 1-Trichloroethane	1.15	2.78	0.43	0.76
	1.83	0.31	0.65	0.45

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CONCLUSIONS

The following conclusions may be drawn from this study:

1. All of the carbons studied showed measurable uptakes of benzene, acetaldehyde, and 1,1,1-trichloroethane.
2. The adsorption of all the compounds on the three carbons was similar—in the range of 10^{-8} to 10^{-6} gmol/g.
3. A packed bed simulation showed that breakthrough occurs very quickly in the shallow (6 in or 15 cm) filters currently marketed for odor control.
4. Carbon adsorption may be applicable for "event control," i.e., sudden surges of concentration caused by spills or leaks.

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DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: In a computer room with laser printers, which emit very heavy ozone, which type of air cleaner would you recommend and where would you locate it?

K. Ramanathan, Research Triangle Institute, Research Triangle Park, NC: I am not sure. Carbon may or may not

work. You would need an efficient collection system, e.g., a hood, around the printer in order to draw the contaminated air into the cleaner.

Arthur E. Wheeler, Wheeler Engineering Co., Towson, MD: Please comment on the potential efficacy of carbon absorption in conjunction with or in lieu of bake out (90° to 100°F) to remove VOCs in new buildings prior to occupancy or following repainting or installation of new carpeting. VOC concentration data under such circumstances are unknown.

Ramanathan: It is difficult to say without knowledge of the exact concentrations and compounds. I would guess that carbon adsorption would definitely be more effective than in standard in-duct use.

Hal Levin, Hal Levin & Associates, Santa Cruz, CA: Was this research the same work reported by Dr. Ensor at IAQ '88?

Ramanathan: Yes. This is an expanded version of the VOC cleaner aspects of the work. Dr. Ensor's paper took a broader view of air cleaner technologies and discussed this aspect briefly.

Levin: You suggested that proper design should be done to use carbon filters. Please describe proper design.

Ramanathan: Systems involving longer contact times between gas and carbon, e.g., pressure swing adsorption systems, might work. Systems based on short cycle time with alternate adsorption and regeneration may also work. Regeneration may present a problem at the low concentrations present in indoor air since chemisorption on the carbon may occur. All the above options will be capital- and energy-intensive and need to be investigated carefully.

Levin: What were the results for acetaldehyde and 1,1,1-trichloroethane?

Ramanathan: Capacities were low and, as the table showing Model I results indicates, breakthrough occurs very quickly.

THE EFFECTIVENESS OF AIR CLEANERS USING AN ENVIRONMENTAL TOBACCO SMOKE MATERIAL BALANCE MODEL

R.A. Jaisinghani G.L. Ruth N.J. Bugli

ABSTRACT

Using a contaminant material balance model, the effectiveness of six air cleaners has been evaluated for a typical restaurant, lounge, and office. The contaminant balance model takes into account particle removal by air cleaners, particle decay due to sedimentation and other mechanisms, and ventilation. The six air cleaners evaluated include an ionizing electrically stimulated filter (IESF), electrostatic precipitator (ESP), two 95% DOP hospital"-type filters, a HEPA filter, and a 95% ASHRAE filter. The results show that air cleaner effectiveness in various applications can be directly related to the product of the 0.3 μm particle removal efficiency and the air cleaner flow rate (referred to as the effectiveness factor). The IESF device was the most effective air cleaner, followed by (in descending order) the 95% DOP hospital-type filters, the 95% ASHRAE filter, the ESP, and the HEPA filter.

INTRODUCTION

Current public interest in the indoor environment and the related health and annoyance aspects of environmental tobacco smoke (ETS) have led to increased use of indoor air cleaners in residential and commercial buildings. A variety of different types of air cleaner products are available to the end user. The cleaning efficiency of these devices is typically specified by at least one of two different test methods: ASHRAE 52-76 and the 0.3 μm DOP. The ASHRAE dust spot test efficiency is the removal efficiency of *local* atmospheric aerosol, while the DOP method focuses on 0.3 μm particle size removal efficiency. Further confusing the proper selection of air cleaners is the fact that air cleaner particle removal efficiency *alone* does not relate to effectiveness in a particular application.

The air cleaning effectiveness for a specific application depends not only on the particle removal efficiency of the device at various particle sizes, but also on the airflow rate of the device; the ventilation flow rate; the ETS generation rate; ETS particle removal via sedimentation, diffusion, and coagulation; and on the cleanliness of the ventilation air. Here it is assumed that the air distribution aspect is adequately addressed. The effect of all these factors can be determined by laboratory studies, but at high expense. Offermann et al. (1985) have conducted a laboratory study limited to portable air cleaners. However, they did not investigate all the above factors and their impact on air cleaner performance for the range of diverse applications such as lounges, restaurants, offices, and residential buildings.

This study attempts to fill this need by utilizing an ETS specific material balance (Appendix A), assuming uniform ETS concentration in the area of interest. The approach here is to use experimentally determined particle size efficiencies of six classes of air cleaners/filters and to use this as input for the ETS material balance in order to determine the effectiveness of air cleaners as a function of the previously discussed variables.

A previous study by Turk (1963) used a similar material balance model for odor vapors. However, Turk's work does not take into accouont particle decay due to sedimentation, diffusion, and coagulation since it is concerned with vapors. This model takes into account particle removal via sedimentation, diffusion, and coagulation (and other possible mechanisms) by using a particle decay rate constant (K) calculated from the chamber measurements of Offermann et al. (1985). It is important to note that these measurements were done for a low air exchange rate. Further, in rooms of different geometry, airflow patterns, and contents this decay rate constant could vary. However, for most applications the particle removal rate due to air cleaners should significantly exceed the natural decay rate. Hence, for the purpose of comparing air cleaners, this approach (using the value of K from Offermann et al. [1985]) is justified. A more rigorous model (published very recently, after this work was completed) by Nazaroff and Cass (1989) takes into account most mechanisms of particle deposition onto surfaces and also considers the effect of coagulation on the changing size distribution of ETS. It should be noted that Nazaroff and Cass also utilize the particle decay measurements of Offermann et al. (1985) for the evaluation of their model. Their results also support the fact that particle removal due to filtration and ventilation far exceeds the removal via natural decay mechanisms.

It should be noted that on-site experimental confirmation of this material balance model in lounges, restaurants, etc., is next to impossible due to the continuously changing number of smokers (ingression rate) and other factors. Further note that this study is limited to evaluating air cleaner devices in terms of ETS and other particulate matter (such as bacteria, moisture aerosols containing viruses, etc.) only, and does not address the issues related to gaseous contamination due to ETS.

EXPERIMENTAL DESCRIPTION

Experimental Setup

The object here was to measure the *single-pass* efficiency (at 0.3 μm) of the various air cleaners. This information was then used in the material balance model. A simple schematic drawing of the test setup is shown in Figure 1. All experiments were performed in a temperature- and humidity-controlled aerosol filtration laboratory capable of maintaining temperature at 70°F ± 2°F and relative humidity at 50% ± 5%. The laboratory has three separate test flow systems, with a combined flow range of 25 to 5000 m³/h. Each system is equipped with appropriate flow- and pressure-measuring instrumentation. Further, each test flow system has been eval-

A. Jaisinghani is manager, corporate research and development, G.L. Ruth is business development manager, and N.J. Bugli is senior research engineer, American Filtrona Corp., Richmond, VA.

TABLE 1

Efficiencies and Effectiveness Factors of Air Cleaners

Type	Rated Efficiency %	Flow Rate (scfm) Q	Measured Eff. % (at 0.3 Um DOP) (N × 100)	Pressure Drop "WC	Effectiveness Factor N × Q (scfm)
1) ESP	99% ASHRAE	800 1200	70.7% 50.1%	0.08" 0.16"	566 601
2)* 6" DEEP AL SEPARATORS	Approx. 95% DOP	850	97%	0.5"	825
3)* 2" DEEP (SEPARATORLESS) MINI-PLEAT	Approx. 95% DOP	850	97.4%	0.56"	828
4)* 2-3/4" DEEP SEPARATORLESS MINI-PLEAT HEPA	99.99% DOP	350	99.97%	0.5"	Approx. 350
5)* 6" DEEP FIBER GLASS MAT	90–95% ASHRAE	800	81.2%	0.52"	650
6)* 1-3/4" DEEP IESF	99.9% DOP	1200	99.9%	0.45"	1199

*ALL FILTER ELEMENTS WITH approximately 4 FT.^{2} CROSS SECTIONAL AREA.

uated for aerosol loss characteristics. This is accomplished by measuring particle counts at various sizes at the influent and effluent sections of the ducts at the lowest flow rate at which the system will be used. The laboratory has approximately 1000 ft^2 floor area with about a 10-ft-high false ceiling.

Efficiency Measurement

All the air cleaners were challenged using cold polydisperse DOP aerosol. The polydisperse aerosol was generated using an atomizer. A special aerosol dispersion "cross" feeder and a "cross" sampler were utilized to result in a well-mixed and average upstream sample. A sharp edge sampler was used downstream. This was adequate since the downstream aerosol was uniformly mixed. Both upstream and downstream particle counts were measured using a light-scattering optical particle counter with 0.3 μm particle size sensitivity. The optical particle counter was coupled with a suitable dilution system capable of a 350:1 dilution ratio. The output of the optical particle counter was interfaced with a realtime data acquisition computer system with software for automatic data analysis.

Six types of air cleaners/filters were used in this study:

(1) An electrostatic precipitator (ESP) rated at 99% ASHRAE dust spot efficiency. This is a single-collection-stage Penney-type ESP that has two collector cells in parallel. Each cell consists of 58 plates, 19 in by 4 in deep spaced 0.187 in apart. The measured ionizer and collector cell voltages are 9.4 kV and 4.2 kV, respectively.

(2) A 6-in-deep aluminum separator filter element, with 95% efficiency at 0.3 μm DOP. This is commonly referred to as a "hospital"-type filter.

(3) A 2-in-deep string separatorless mini-pleat filter element, with 95% efficiency at 0.3 μm DOP, also referred to as a "hospital"-type filter.

(4) A 2 3/4-in-deep mini-pleat separatorless HEPA filter element, with 99.99% efficiency at 0.3 μm DOP.

(5) A 6-in-deep fiberglass mat-type element rated at 90% to 95% ASHRAE 52-76 efficiency.

(6) An ionizing, electrically stimulated filter (IESF) rated at 99.9% at 0.3 μm DOP, with a 20.5 in by 28 in filter element.

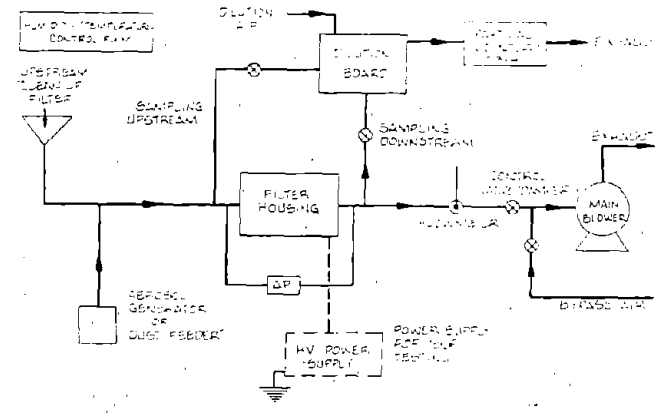

Figure 1 Experimental test setup

Item 1—ESP—is the most commonly used device, while item 6 is a newly introduced device described by Jaisinghani and Bugli (1988a, b). Briefly, this device utilizes a highly permeable, low-mechanical-efficiency filter paper with electrical enhancements of its efficiency to high levels. The flow and contaminant-holding properties of the IESF far exceed those of equivalent efficiency mechanical filters.

It should be noted that air cleaners 1 (ESP) and 6 (IESF) were tested as complete units with integral blowers. Both units fit into a 2 ft by 4 ft ceiling panel. These units were also evaluated for single-pass efficiency in the test ducts by disconnecting the blowers (i.e., testing the ESP ionizer and cells, and IESF at rated voltage without using the blowers) and by using the test duct blower to maintain the rated flows. Both methods resulted in almost identical values of efficiency. The other mechanical filter units—2, 3, 4, and 5—were evaluated in a well-sealed generalized filter housing. This eliminated the need to purchase individual units without sacrificing the accuracy of the efficiency measurements. All the filter units (2-4) were of approximately the same size, 2 ft by 2 ft cross section. The IESF filter also had approximately the same cross-sectional area. Items 2-4 were evaluated at flow rates such that the pressure drop across the clean filter elements

as approximately 0.5 in w.c. This is typical since most indoor r pollution control devices use low-pressure blowers due to ost, size, weight, and especially noise considerations. The essure drops for units 1-6 are shown in Table 1.

ESULTS AND DISCUSSION

fficiency of Various Air Cleaners

Table 1 shows the measured efficiency and flow rates of e six air cleaner units. The measured efficiency is in terms 0.3 μm DOP particle size. This particle size is relevant for TS removal applications. Hinds (1978) reported that the edian size of ETS ranges from 0.1 to 0.5 μm, with the mass edian diameter typically being 0.37–0.52 μm. Based on the ore recent work by Chang et al. (1985) and Ueno and Peters 986), the number and mass median diameters for sidestream noke are 0.1 μm and 0.16 μm, respectively. The mainstream noke is bimodal, the lower mode having a number average 0.24 μm and a mass average of about 0.26 μm. Hence, it advantageous to utilize the 0.3 μm DOP efficiency, espeally due to its common use in the filtration industry.

Based on the material balance model (Appendix A), the fectiveness of an air cleaner can be approximately expressed the product of its efficiency, N, and the flow rate, Q. Sutton al. (1964) have also shown this to be of primary importance an essentially closed system with good mixing. Table 1 also ows the effectiveness factor, NQ, which is the product of e flow rate times the fractional 0.3 μm efficiency of the rious air cleaners. As is clear from Appendix A, this is *proximately* the equivalent of the *additional* ventilation rate quired to achieve the same particulate concentration in the om without use of the air cleaner. The higher the value of Q, the higher the effectiveness of the air cleaner. In this se, the IESF exhibited the highest NQ (1199 scfm), with e 95% DOP filters (hospital types) being second highest Q is approximately 825 scfm). Within this range of flows, e mechanical filters had little change in efficiency with reect to flow rate (since the change in capture by interception compensated by the change in efficiency due to the diffusion echanism). However, the ESP's efficiency, as expected, was duced at higher flow rates. Consequently, there was little ange in the NQ value for the ESP (566 to 601 for a flow te change of 800 to 1200 scfm). On the other hand, the ficiency of the IESF is only marginally affected by the flow te in this range (600-1200 scfm) of operation. At 600 scfm e IESF has a measured efficiency (at 0.3 μm DOP) of .95%, while at 1200 scfm the 0.3 μm DOP efficiency is .9%. Note that the IESF has approximately the same filter oss-sectional area as the other mechanical filters.

eneralized Effectiveness of Air Cleaners

Particle Decay Rate and Particle Generation. The ETS rticle material balance model is developed in Appendix A. similar material balance model has been used by Whitby al. (1983). It is important to note that the concentration vel, C, is an average concentration since the model assumes at no spatial concentration distribution exists. In order to e this model for evaluating the air cleaner effectiveness for TS, values for the particle decay rate constant K and particle neration rate need to be determined.

The decay or loss rate constant K should depend on room e, particle type and size distribution, airflow patterns, and ntilation, among other factors. In the experimental work Offerman et al. (1985), the ETS concentration change with spect to time, in a chamber, was used to determine the value of K (0.1 h^{-1}). It should be noted that Offermann et al. used 0.1 ach ventilation. In this study, although the model is applied to higher ventilation rates, the value of K = 0.1 h^{-1} has been taken as a constant. When air cleaners with high recirculation rates (i.e., V/Q is low, Equation 2, Appendix A), or when Qv, the ventilation flow rate, is significantly greater than N_eQ, the solution to the material balance equation (Equation 4, Appendix A) becomes relatively insensitive to the actual value of K, since O (Equation 4, Appendix A) is not significantly affected. This is especially true for high-efficiency (N is approximately 0.95) air cleaners. For example, consider an air cleaner with efficiency N of approximately 0.95 operating at a recirculation rate of 5 per hour. Here, N_e = 0.97 for K = 0.1 h^{-1} while N_e = 0.99 for K = 0.2 h^{-1}.

The amount of particulate matter generated per cigarette varies in the reported literature. In this study, a value of 12 mg/cigarette has been chosen based on our own internal experience. This is in close agreement with the work of Chang et al. (1984), who obtained 11.2 mg/cigarette. The average rate of cigarettes smoked is taken to be two cigarettes per hour per smoker throughout this study. This is based on the work of Cain et al. (1983), among others. Further, it is assumed that besides incoming particulate matter from the ventilation airflow, all particulate matter generated is due to ETS. The incoming ventilation particulate concentration is taken to be 154 $\mu g/m^3$, which is the value commonly used for urban areas with populations of about 10^6 (Hinds 1982). With these values for particle generation and decay rate constants, we are now in a position to apply the material balance model.

Generalized Results. Noting that the equilibrium concentration (Equation 6, Appendix A) is independent of the room/area size and volume and is only dependent on the net ingression rate, I, and equivalent ventilation rate, O, the model results can be expressed in generalized terms. Note that the room volume only affects the time to reach equilibrium concentration.

Figure 2 is a three-dimensional plot of the equilibrium concentration, C_{eq}, plotted against N_eQ and number of smokers. Since this is a generalized pictoral view, a hypothetical ventilation flow rate, Qv = 5 scfm/person, assuming 35% smokers, has been used here. As expected, C_{eq} increases with an increase in the number of smokers, but this increase is limited as the N_eQ value of the air cleaner increases. Noting that N_eQ approximately = NQ (the effectiveness factor), the effectiveness of three hypothetical air cleaners with identical flow rates (but having different efficiencies of 50%, 90%, and 99.95%) is shown in Figure 2. Clearly, for a high number of smokers, air cleaners with high NQ values are required for effective air cleaning.

In Figure 3, the equilibrium concentration, C_{eq}, is plotted against the "effective" ventilation rate, O, for various constant net ingression rates, I, using Equation 6, Appendix A. Figure 3 shows that as O increases, the equilibrium concentration asymptotically approaches a limiting value. Practically, there is a minimum attainable concentration, which is higher for higher net ingression rates. This limiting concentration is also dependent upon the value of ventilation air particle concentration, C_o.

The time to clean a previously contaminated area to a given level is given by Equation 5, Appendix A. This is illustrated in Figure 4 for a 425 m^3 room contaminated to an initial concentration of 1200 $\mu g/m^3$, using a ventilation flow rate of 425 m^3/h. The time-based concentration curves are

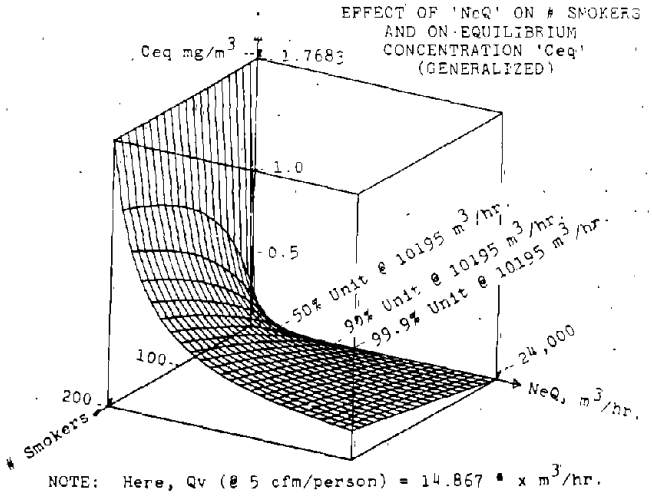

Figure 2 Three-dimensional plot illustrating the effect of number of smokers (generation rate) and N_eQ (approximate effectiveness factor, NQ) on equilibrium concentration. Q_v = number of smokers x 14.867 m^3/h

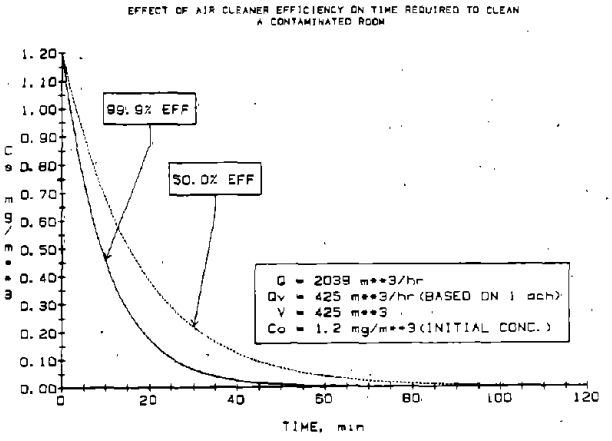

Figure 4 Effect of air cleaner efficiency on time required to clean a contaminated room

shown for 50% and 99.9% efficient (at 0.3 μm DOP) air cleaners, both operating at the same flow rates (2039 m^3/h). Clearly, time for cleaning a room to a desired concentration is shorter for the 99.9% efficient unit. This cleaning speed should be qualitatively related to the effectiveness of devices in terms of quickly eliminating the irritation aspects of high-concentration sidestream cigarette smoke.

Specific Applications

The ETS material balance model has been used to evaluate the air cleaners described in Table 1 in three specific situations. The three situations are close approximations of actual field installations of the IESF. These situations, described in detail in Table 2, are (a) a medium-sized restaurant, (b) a typical lounge, and (c) a large office. The medium-sized restaurant is analyzed in detail using ventilation rates from 5 to 30 scfm/person (based on maximum occupancy). Due to brevity requirements, the other three situations are analyzed only at the 5 scfm/person ventilation rate.

It is important to note here that, based on the work of Weber (1984), we can assume that in most situations and for

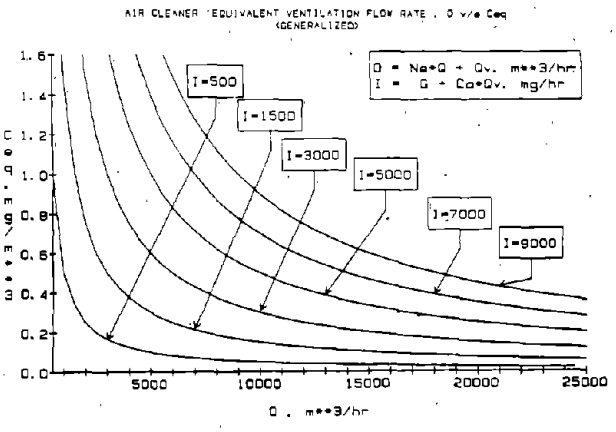

Figure 3 Effect of air cleaner "equivalent ventilation rate," Q, on equilibrium concentration

TABLE 2

Description of Specific Applications of Material Balance Model

Variables (Input Data)	APPLICATION Med. Size Restaurant	Typical Lounge	Large Office
a) Area (sq. ft.)	1500	2670	4000
b) Room Volume (cu. ft.)	15,000	21,360	36,000
c) Design Occupancy (# of people)	120	220	50
d) % Smokers	30%	50%	30%
d) # of Smokers	36	110	15
f) Actual Ventilation Flow (cfm)	600 1800 3600	1100	250
g) Equivalent ach	2.4 7.2 14.4	3.09	0.42
h) Equivalent cfm/person	5.00 15.00 30.00	5.00	5.00

most people eye and membrane irritation *starts* developing at ETS concentration levels above approximately 200 $\mu g/m^3$. This level, therefore, has been chosen as an irritation threshold limit and air cleaner performance is evaluated on this basis.

Detailed Analysis for a Medium-Sized Restaurant. The performance characteristics of the various devices (Table 1) are illustrated in Figures 5 and 6. Figure 5 shows the equilibrium concentrations obtained as a function of the number of units* of the devices (Table 1) at maximum occupancy with an existing ventilation rate of 5 scfm/person. Based on the previously discussed irritation onset level (200 $\mu g/m^3$), the corresponding required number of units can be determined by reading the abscissa values (in Figure 5) at C_{eq} = 200 $\mu g/m^3$. For example, four ESP units are required, as opposed to

*Note that each of the devices in Table 1 has a corresponding airflow rate shown in Table 1. Hence, the number of units can be related to the total flow rate for each type of device.

two IESF units, to achieve this threshold concentration limit. Note that both these ESP and IESF devices have the same airflow rate (1200 scfm).

Figure 6 is the plot for C_{eq} vs. the number of smokers in the restaurant with a 5 scfm/person ventilation rate (using maximum occupancy). For all air-cleaning devices two units have been used in this situation (i.e., the total flow rate for each device is twice that of the corresponding value in Table 1). Once again based on the 200 $\mu g/m^3$ threshold limit, the IESF is clearly the most efficient device, able to handle the maximum number (36) of smokers while maintaining the ETS concentration level below 200 $\mu g/m^3$. The ESP and the 95% ASHRAE filter can maintain this level only up to half the maximum number of smokers. The hospital-type (95% DOP) filter on the other performs to this level up to about 25 smokers and hence is the second most effective device. The HEPA filter can achieve this threshold limit to only about 11 smokers due to its low flow rate (i.e., low NQ value). Also shown, in Figure 6, is the "no air cleaner, 5 scfm/person ventilation only" situation. In this case, with approximately 3 smokers, the concentration limit can exceed the 200 $\mu g/m^3$ threshold limit; at maximum occupancy, a highly irritating situation exists with an ETS equilibrium concentration of 1001 $\mu g/m^3$.

The effect of ventilation rate on C_{eq} is shown in Figure 7. Using 5, 15, and 30 scfm/person (using maximum occupancy), the effectiveness of the different devices and ventilation rate alone is illustrated at maximum occupancy. Clearly the performance differences between the air cleaner devices diminishes as the ventilation flow rate increases, with the IESF still having a slight edge over the other devices. Another way to view these data (Figure 7) is to note that devices having higher NQ values require less ventilation for satisfactory performance. This would result in a net savings in heating and air-conditioning costs. For example, the IESF can maintain lower ETS levels with a 5 scfm/person ventilation rate than all the other devices operating with a ventilation rate based on 30 scfm/person. Of course, ventilation rates must also be based on gaseous contaminants and not on particulate matter only.

Typical Lounge. Our field experience with existing (not new construction) lounges shows that, at best, ventilation rates of 5 scfm/person, based on maximum occupancy, are utilized. Hence, the application of the material balance model for the evaluation of the air cleaner devices in lounges uses this ventilation rate. The lounge occupancy, size, and other constants and assumptions are shown in Table 2.

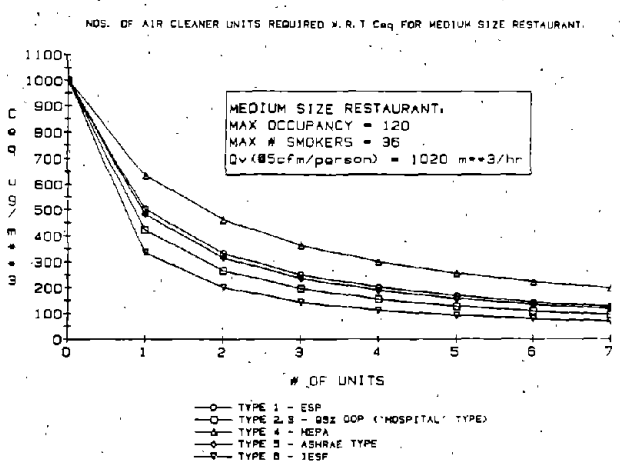

Figure 5 Effect of number of air cleaner units on equilibrium concentration for medium-sized restaurant

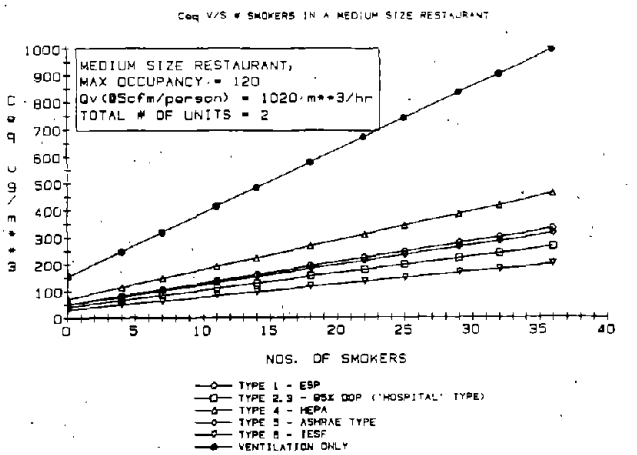

Figure 6 Equilibrium concentration as a function of number of smokers in restaurant

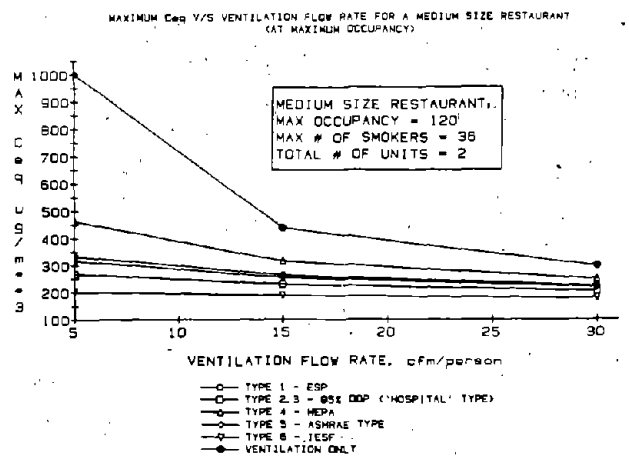

Figure 7 Equilibrium concentration at maximum restaurant occupancy at various ventilation flow rates

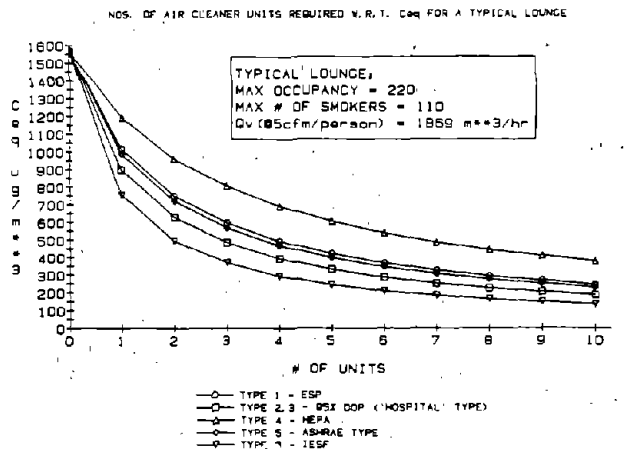

Figure 8 Effect of number of air cleaner units on equilibrium concentration in lounge

Figure 8 for the lounge corresponds to Figure 5 for the restaurant case. In this high occupancy density application, about six IESF units would be required to approach the threshold concentration limit *at maximum occupancy*. The next best unit (hospital-type 95% DOP filter) would require nine installed units. This is not practical or economical since this means that about every 300 ft² of floor space would require one air cleaner. This situation is significantly worse for the other air cleaner devices (Figure 8). Practically, there is room for a maximum of five to six units in this application.

Choosing six units of each type of air cleaner with the existing fixed 5 scfm/person ventilation rate (based on maximum occupancy), the effect of the number of smokers on the air cleaner performance is shown in Figure 9. Only the IESF unit can maintain the ETS concentration at or below the 200 μg/m³ threshold limit at maximum occupancy (110 smokers). The 95% DOP filter (hospital-type) can maintain this limit to about 77 smokers, while the ESP can handle up to 55 smokers at this level. The 95% ASHRAE filter can operate at this threshold level for a maximum of approximately 60 smokers and the HEPA filter, due to its low flow characteristics, would exceed the threshold limit beyond 33 smokers in the lounge. Note, in Figure 9, the excessive ETS concentration with the 5 scfm/person ventilation rate only (i.e., no air cleaner used). By increasing the ventilation rate to 30 scfm/person (based on maximum occupancy), the threshold limit can only be maintained up to about 22 smokers in the lounge.

Large Office Area. The material balance has been applied to a large office area (see Table 2) with a 5 scfm/person ventilation flow rate (using maximum occupancy). The required number of units of each type of air cleaner for this application (with maximum occupancy) is obtained from Figure 10. In this case, one IESF unit has approximately the same performance level (C_{eq} = 173 μg/m³) as two of the ESPs. By comparison, one of the 95% DOP (hospital-type) filters results in an equilibrium concentration of 233 μg/m³. Although higher than the IESF, it is still an effective solution in this particular application.

Figure 11 illustrates the effect of the number of smokers on the ETS equilibrium concentration for one unit of each type of device. Also, the effects of the existing (5 scfm/person) and 30 scfm/person ventilation rates only (i.e., no air cleaner used) are shown in Figure 11. At maximum occupancy, the IESF results in a concentration level of 173 μg/m³, well below the 200 μg/m³ threshold limit, while the 95% DOP (hospital-type) filter is also effective, maintaining the ETS concentration at 233 μg/m³. The ESP is effective, in this sense, only to about 10 smokers in the office. The existing ventilation rate (5 scfm/person) is entirely ineffective without air cleaners, while the higher (30 scfm/person) ventilation rate is effective, without air cleaners, to about six smokers in the office.

SUMMARY

In most applications, properly sized air cleaners can be used at existing ventilation rates (5 scfm/person, based on maximum occupancy) in order to control the irritating aspects of the particulate phase of ETS. Gaseous phase considerations may require higher ventilation rates. Of the devices evaluated here, the ionizing electrically stimulated filter (IESF) air cleaner resulted in the best performance or room cleanliness level when an equal number of units was considered. The 95% DOP (hospital-type) filter was next in terms of effectiveness, followed by the 95% ASHRAE filter and ESP. The HEPA filter was ineffective due to its low flow characteristics. In the three applications considered (lounge, restaurant, and office), in order to match the performance level of the IESF, more units of the other types were required.

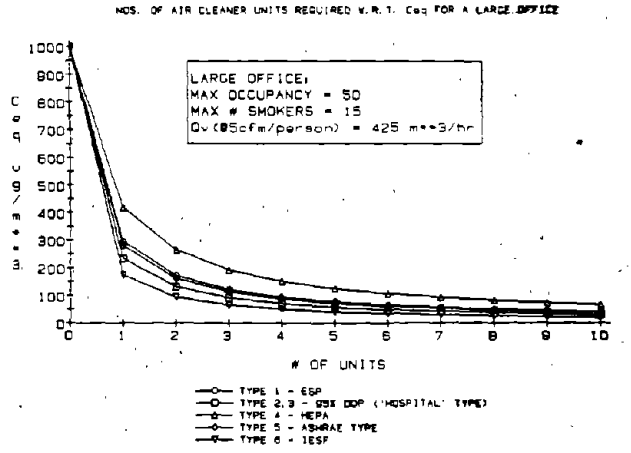

Figure 10 Effect of number of air cleaner units on equilibrium concentration in office

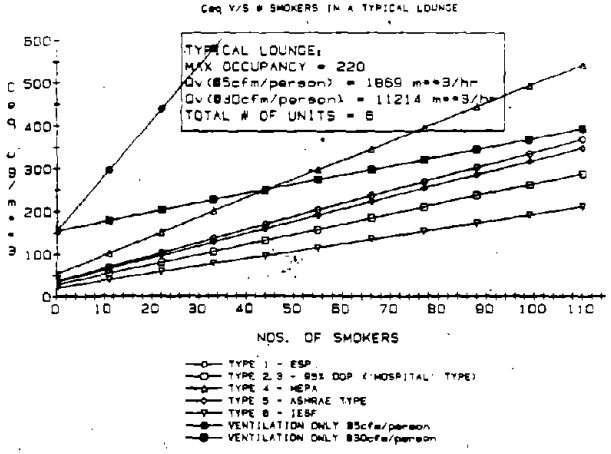

Figure 9 Equilibrium concentration as a function of number of smokers in lounge

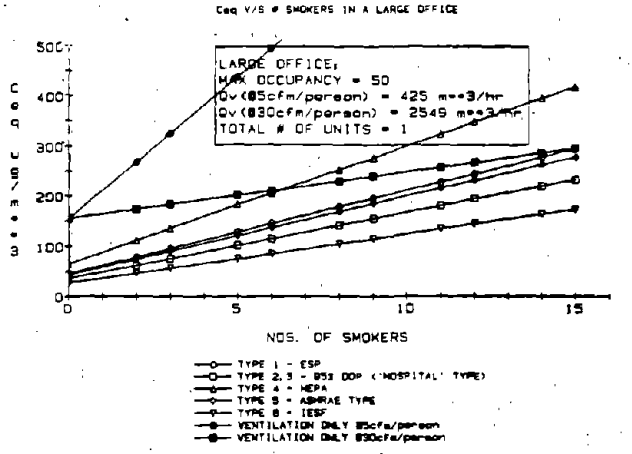

Figure 11 Equilibrium concentration as a function of number of smokers in office

A good measure of the effectiveness of a single unit of a particular type of air cleaner is the product of its 0.3 μm DOP efficiency and its flow rating. This product, referred to as the effectiveness factor, has also been utilized by Sutton et al. (1964). The higher this value, the more effective the air cleaner.

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NOMENCLATURE

C = concentration at time t (mg/m³)
C_a = ventilation air particulate concentration (mg/m³)
C_{eq} = equilibrium concentration reached (mg/m³)
C_o = initial room air particulate concentration (mg/m³)
G = particulate generation rates (mg/h) (depends on number of smokers)
I = total ingression rate of contaminant = $(G + Q_v C_a)$ (mg/h)
K = particulate decay rate constant (h⁻¹)
N = air cleaner efficiency
N_e = effective air cleaner efficiency
N_eQ = product of effective air cleaner efficiency x volumetric flow rate of the air cleaner; effective air-cleaning rate (m³/h)
NQ = effectiveness factor (m³/h)
O = equivalent ventilation flow rate such that the room is maintained at the same equivalent concentration without an air-cleaning device = $(N_eQ + Q_v)$ (m³/h)
Q = total rated flow of air cleaner (m³/h)
Q_v = total ventilation flow rate (m³/h)
t = time (h)
V = volume of indoor space/room (m³).

APPENDIX A
Material Balance Development

Ignoring spatial concentration variation, a material balance equation is set up as follows:

$$V\frac{dC}{dt} = -NQC + G - Q_v(C - C_a) - VKC \quad (1)$$

The first term on the right-hand side of Equation 1 is the particle removal rate by the air cleaner, the second is the generation rate, the third is the net removal rate by ventilation and the fourth term is the particle decay rate, expressed in terms of the decay rate constant K as per Offermann et al. (1985).

Equation 1 can be expressed as:

$$\frac{dC}{dt} + \frac{(N_eQ + Q_v)}{V}C = (G + Q_vC_a)/V$$

where

$$N_e = N + \frac{KV}{Q} \quad (2)$$

Note that V/Q is the inverse of air turnover rate.

The solution to this differential equation is:

$$e^{\frac{(N_eQ + Q_v)t}{V}}C = \frac{(G + Q_vC_a)\,e^{[(N_eQ + Q_v)t]/V}}{N_eQ + Q_v} + K''' \quad (3)$$

Applying boundary conditions $C = C_o$ at $t = 0$

$$K''' = C_o - \frac{(G + Q_vC_a)}{(N_eQ + Q_v)}$$

therefore,

$$C = \frac{I}{O}\left[1 - e^{\frac{-(Ot)}{V}}\right] + C_o e^{\frac{-(Ot)}{V}} \quad (4)$$

where:

$$I = (G + Q_vC_a)$$
$$O = (N_eQ + Q_v)$$

Note that I is the net ingression rate, while O is the equivalent ventilation flow rate that would be required to achieve the same room concentration.

The second term on the right-hand side of Equation 4 is the exponential decay if there was no continuous ingression, i.e., the decay of particle concentration in a room that is previously contaminated and the contamination source is eliminated. The time to achieve a certain concentration, C, is then

$$t = \frac{V}{O} \ln [(C_o - I/O)/(C - I/O)] \quad (5)$$

Note that the numerator of the logarithmic term is the initial net removal rate, while the denominator is the similar net removal rate at the desired or specific concentration.

The equilibrium concentration can be calculated from Equation 4 by applying boundary conditions at $t = \infty$, $C = C_{eq}$

$$C_{eq} = \frac{I}{O} \quad (6)$$

Note that this is simply the ratio of the total contaminant ingression rate to the "equivalent ventilation" rate. Further, note that for low particle decay rates (or large air cleaner turnover rates), the equivalent concentration does not depend on the room volume.

DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: If you had tested using 10 or 15 cfm instead of the 5 cfm do you feel the filters could have been smaller?

R.A. Jaisinghani, American Filtrona Corp., Richmond, VA: By increasing the ventilation rate, the size of the filters could be reduced while maintaining the same effectiveness or performance. The reduction in filter size can be calculated by keeping O = (NeQ + Qv) = constant.

Ole Fanger, Technical University of Denmark, Lyngby, Denmark: Our studies in Denmark show that removal of the particles from environmental tobacco smoke did not change the odor, irritation, or acceptability of the air. But particles on walls in the space or on filters can be a substantial source of gaseous emission. Have you any practical solution to this problem?

Jaisinghani: Regarding the comment on the effect of the ETS particulate phase on irritational aspects, I must point out that Weber's results contradict this statement. The ETS particulate phase consists of many irritation-causing components. It is important to use a significantly higher efficiency filtration device to be sure that the particulate phase is removed for such studies aimed at evaluating the irrational aspects of ETS. This is important due to the extremely small size of ETS.

No, as yet there is no practical solution (besides ventilation) for the removal of the vapor phase of ETS. It is important to note that while a filter can accumulate part of the gas phase that may emit from the ETS particles, this in no way contributes to the time average concentration of such emissions. Our experience has not shown this to be a problem in various air cleaner applications.

ENHANCING AIR PURIFICATION

A.H. Frey, Ph.D.

ABSTRACT

Although filters and charcoal beds in ducts effectively remove many room contaminants that are carried to them via the ducts, a large proportion of the contaminants that are found in room air do not reach them. The reason, as shown in an earlier paper, is that the motion of contaminants less than one micron in size is determined more by the normal electrical forces in any room than by the air currents. Thus, a large proportion of the contaminant load in a room tends to plateout on people and objects. This results in adverse effects on health and comfort. What is needed is a means to enhance the natural process of aerosol coagulation to increase particle size so air currents can more readily entrain and return the particulates to the filters via the ducts.

Research that shows a means of enhancing aerosol coagulation, the use of in-duct complex electrical fields, and its application is described in this report. First, the relevant physics is summarized. Then the results of two experiments testing and verifying this means to enhance coagulation are detailed. Then an experiment using groups of people exposed to tobacco smoke, a ubiquitous environmental contaminant, is reported. Research using other common building contaminants, i.e., formaldehyde and sulphur dioxide, is also reported. Statistical analyses of these data show that removal of gaseous contaminants can also be enhanced by these means. The substantial implications for health and comfort are then discussed.

INTRODUCTION

Although filters and charcoal beds in ducts effectively remove many room contaminants that are carried to them via the ducts, a large proportion of the contaminants that are typically found in room air do not reach them. The reason, as shown in an earlier paper, is that the motion of contaminants less than one micron in size is determined more by the normal electrical forces in a room than by air currents, a well-established fact of physics (Frey 1986a). Thus, a large proportion of the contaminant load in a room tends to plateout on people and objects. This results in adverse effects on health and comfort.

What is needed is a means to enhance the natural process of aerosol coagulation so as to more rapidly increase particle size. Then air currents will be the dominant force, and can return the particulates to the filters via the ducts.

In this article, some of the basic physics that determine whether contaminants are returned to a filter via the ducts is summarized. A means of accelerating coagulation of particulates via in-duct complex electric fields is suggested. Then the procedures and results of two experiments testing the suggestion are presented. The findings from these experiments are then extended with a description of experimentation with humans exposed to tobacco smoke. Then a set of complementary experiments with two gaseous contaminants, which absorb and adsorb onto particles, are described. The statistical analyses of the latter experiments show that operation of the in-duct complex electrical fields significantly reduces the room concentration of these gaseous contaminants. The implications for health and comfort are then discussed.

ATMOSPHERIC PHYSICS

Aerosols vary in size, concentration, and settling time. Their salient characteristics are summarized in Tables 1 and 2. More than 98% of particles in room air are one micron or less in size and, as noted in the tables, essentially do not settle out of the air by gravity. The electrical forces are important in controlling these because they are virtually always charged. Aerosols acquire charge by three basic mechanisms: diffusion charging, field charging, and static electrification. The details of these mechanisms can be found in Frey (1986a).

TABLE 1

Characteristics of aerosols

Particle size in microns	Percentage of particles by count	by weight
10–30	< 1	28
5–10	< 1	52
3–5	< 1	11
1–3	1	5
0.5–1	6	2
<0.5	92	1

TABLE 2

Particle setting time in still air

Particle size in microns	Time required to settle 8 feet
100	8 seconds
10	13 minutes
1	19 hours
0.1	79 days
0.01	∞

Given the charged particle generated by a mechanism noted above, consider the effect of the ever-present electrical fields on it. The electric field that exists in the space about a charged object causes a charged particle that is in this space to experience a force, the electrostatic force. Specifically, the force on a particle with n elementary units of charge (e) in an electric field (E) is $F_E = neE$. The field strength at any point in the space is equal to the potential gradient at that point.

Given the charged particle and the electrical field in the space, we can consider more specifically what happens when aerosol particles collide with one another, as they constantly do. They adhere to each other and thus grow to form larger particles with a consequent decrease in number of particles. When the motion of the particles is due to Brownian motion, the growth process is called thermal coagulation. It is a spontaneous and always present phenomenon. When the motion is due to gravity or electrical forces or from aerodynamic effects, the process is called kinematic coagulation. Coagu-

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lation is the most important phenomenon in the interactions in aerosols.

Electrical forces between particles increase coagulation by enhancing the substantial thermal coagulation mechanism. With low intensity and fairly homogeneous electrical fields, collisions of aerosol particles of opposite signs are increased but collisions between particles of the same sign are reduced. The net effect is little change in coagulation for aerosols with Boltzman equilibrium charge distribution. But there can be a significant increase in coagulation of aerosols with a strong bipolar charge distribution or in strong nonhomogeneous fields.

Aerosol particles will attach firmly to any surface they contact, not just to each other. The adhesive forces on micron size particles exceed other forces by orders of magnitude. They are a prime factor in contamination.

The importance of these adhesive forces, which are primarily electrical, in contamination can be seen by considering how high they are compared to removal forces. Adhesive forces are proportional to d, and removal forces are proportional to d^2 for air currents and d^3 for vibration and centrifugal stress. Consequently, the smaller the particle size, the less likely it will be displaced from a surface.

In sum, the electrical characteristics of particles, the normal electrical fields in spaces, and the electrical characteristics of objects and surfaces in the space are some of the primary determinants of contamination.

Given this basic physics, contamination control could be enhanced if coagulation could be accelerated. Thus, larger particles are less influenced by the normal electrical forces in a space and more by the air currents. Thus, they can be more readily carried to the filters via the ducts. Such acceleration should occur if particulates in a duct encounter a complex non-homogeneous electrical field with suitable characteristics.

The objective of the first experiment was to determine if the concentration of respirable particulates in room air, i.e., tobacco smoke, would be influenced by passing the air through a complex high-frequency, high-voltage electric field located in the supply duct.

EXPERIMENT 1

Tobacco smoke consists of respirable-size particulates and gases that are well characterized and can be generated in a simple, reliable manner. Mainstream smoke is that which is inhaled by a smoker; consequently, many of the pollutants are filtered out in the smoker's lungs, i.e., 70% of the particulate manner. Sidestream smoke is the unfiltered smoke emitted from an idling cigarette, cigar, or pipe. It has been found that 75% of sidestream particles remained suspended in a test chamber after 2.5 hours. Their median size is 0.7 microns with no particles greater than two microns. Thus, we used sidestream smoke to test the possibility that specific electric fields in a duct would influence the concentration of particulates in a room.

Experimental Setup and Method

The testing was carried out in a room 2.7 × 4.3 × 2.4 m (9 × 14 × 8 ft) with a floor of vinyl tile and walls and ceiling paneled as shown in Figure 1. The paneling was coated with polyurethane varnish and the joints were sealed with duct tape. The room had its own air-handling system. Air entered the room through supply diffusers at one side, passed across the room, and exited into a duct through return grilles at an air change rate of 21 per hour. In the duct, the air passed sequentially through a 55% ASHRAE-rated filter, three electric field screens, the blower, and then re-entered the room through the supply diffusers. The air in the room was purged to the outside between test runs and replaced by building air. The electric field screens installed in the duct perpendicular to the airflow were 60 × 60 cm (2 × 2 ft), except the center one (screen B), which was 5 cm (2 in) larger. They were spaced 7.6 cm (3 in) apart. The screens consisted of 0.6 cm (.25 in) mesh hardware cloth. Electric field generators supplied a 700 V pp 177 kHz signal that was applied to screen B and also a 25 kV DC signal that was applied to screens A and C. The current was less than 3 ma. No ozone is produced by this system. The data supporting this conclusion are detailed in Appendix A. The mean temperature in the room was 22°C (72°F) and the mean relative humidity was 70% during the testing.

Particle concentration was measured by mass and light scattering. Mass measurement was accomplished with the use of a respirable aerosol mass monitor. The mass monitor collects essentially all respirable particles (0.01 to 10 microns) on a quartz crystal sensor which detects mass concentrations as low as 0.01 mg/m^3 and as high as 50 mg/m^3 on a real-time basis. It was set to continuously take 24-second samples. The teflon tube air intake was located in the center of the room and was held in place by a vertical wooden rod.

The laser light-scattering measurement system consisted of a helium-neon laser, a phototransistor detector, a potentiometric amplifier with a DC offset module and strip recorder, and a digital voltmeter. The laser beam passed diagonally across the room, 107 cm (3.5 ft) above the floor, and impinged upon the phototransistor detector.

The procedure was to purge the room to baseline particulate concentration, generate smoke to increase the particulates to a standard level, stop the smoke production, and then measure the decrease in concentration over the following 30 minutes. An ordered, counterbalanced sequence of 16 test runs was used, as is shown in Table 3. The experiment was replicated twice with comparable results.

TABLE 3

Test sequence used. The x indicates the test condition used in each particular run

Run No.	Filter in	Filter out	Field on	Field off
1	x			x
2	x		x	
3		x	x	
4		x		x
5		x	x	
6		x		x
7	x			x
8	x		x	
9		x		x
10		x	x	
11	x		x	
12	x			x
13	x		x	
14				x
15		x		x
16		x	x	

Specifically, the air-handling system was turned on and the air in the test room purged to the outside until the level of airborne particles in the test room reached a standardized baseline condition. Tobacco smoke was then generated inside the test room at the location noted in Figure 1 with a device that "smoked" cigars, providing sidestream smoke. The

TABLE 4

Overall analysis of variance of mass monitor data. The comparison of electric field on vs. off is denoted by A. B denotes the change in aerosol concentration over time.

Source	SS	df	MS	F ratio	Significance
Between					
A	259	3	86	35.94	< .001
SWG	28	12	2.4		
Within					
B	2953	2	1296	1693.89	< .001
AB	63	6	10	13.82	< .001
B X SWG	18	24	.8		

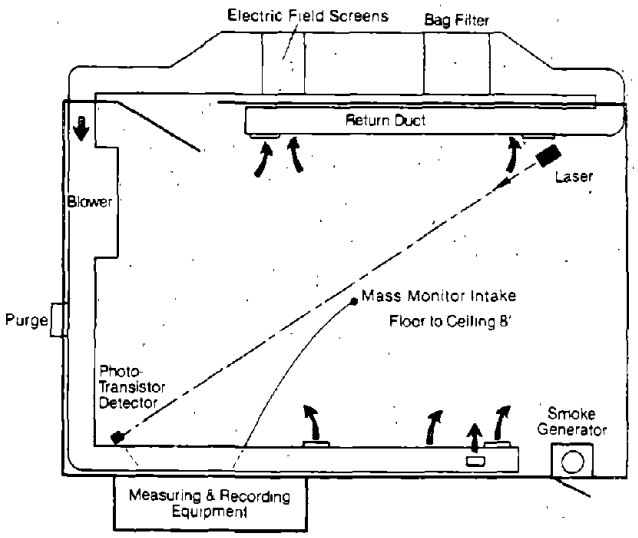

Figure 1 Test facility showing air-handling system and measurement setup

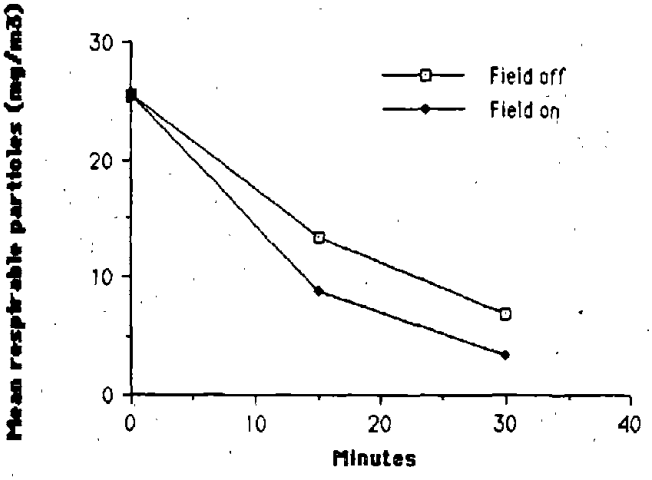

Figure 2 Plot of mean tobacco smoke particle concentration as measured by mass

TABLE 5

Analysis of variance comparing particle mass with electric field on vs. off with a 55% filter in the system. Note that at the start of the runs there were no significant differences between groups in particle mass as per design.

Source	SS	df	MS	F ratio	Significance
Start					
Between	13	1	13	3.88	ns
Within	20	6	3.4		
15 minutes					
Between	43	1	43	51.11	< .001
Within	5	6	.8		
30 minutes					
Between	24	1	24	273.10	< .001
Within	.5	6	.1		

TABLE 6

Analysis of variance of the laser light scattering data with the filter in. The comparison of electric field on vs. off is denoted by A. B denotes the change in aerosol concentration over time.

Source	SS	df	MS	F ratio	Significance
Between					
A	417	1	417	17.37	< .01
SWG	144	6	24		
Within					
B	15603	5	3120	2592.68	< .001
AB	8	5	1.7	1.45	ns
B X SWG	36	30	1.2		

smoke was blown toward the center of the room with a 45 cfm muffin fan. Sufficient cigars (approximately 2) were smoked with the device to bring the smoke density in the test room to a standard level (i.e., 25 mg/m^3). At this point, the smoke generator was turned off and a 30-minute run was started. The smoke density was measured with the mass monitor at the start of a run, at 15 minutes into the run, and at the end of the 30-minute run. Light-scattering measurements were made every 5 minutes during a run. At the end of each run, the room was purged to baseline level and the next test in the series was then begun.

Results

The mean respirable mass measured during the runs in the different conditions is shown in Figure 2. The significance of the differences between the means was tested with an overall analysis of variance and is summarized in Table 4. The differences between air treatment conditions (A) were significant at the .001 level. The general reduction with time in the measured particulates (B) was also significant, as would be expected, since no new smoke was added to the room during a run.

Since there were statistically significant differences in treatment effects (A), more detailed analyses of the data were appropriate. A one-way analysis of variance comparing the test conditions at the start of the runs showed no significant differences among treatment groups. Thus, as intended, the tests for the different treatment conditions all started with the same particulate mass in the room. The treatment conditions at the 15-minute and 30-minute points were signifi-

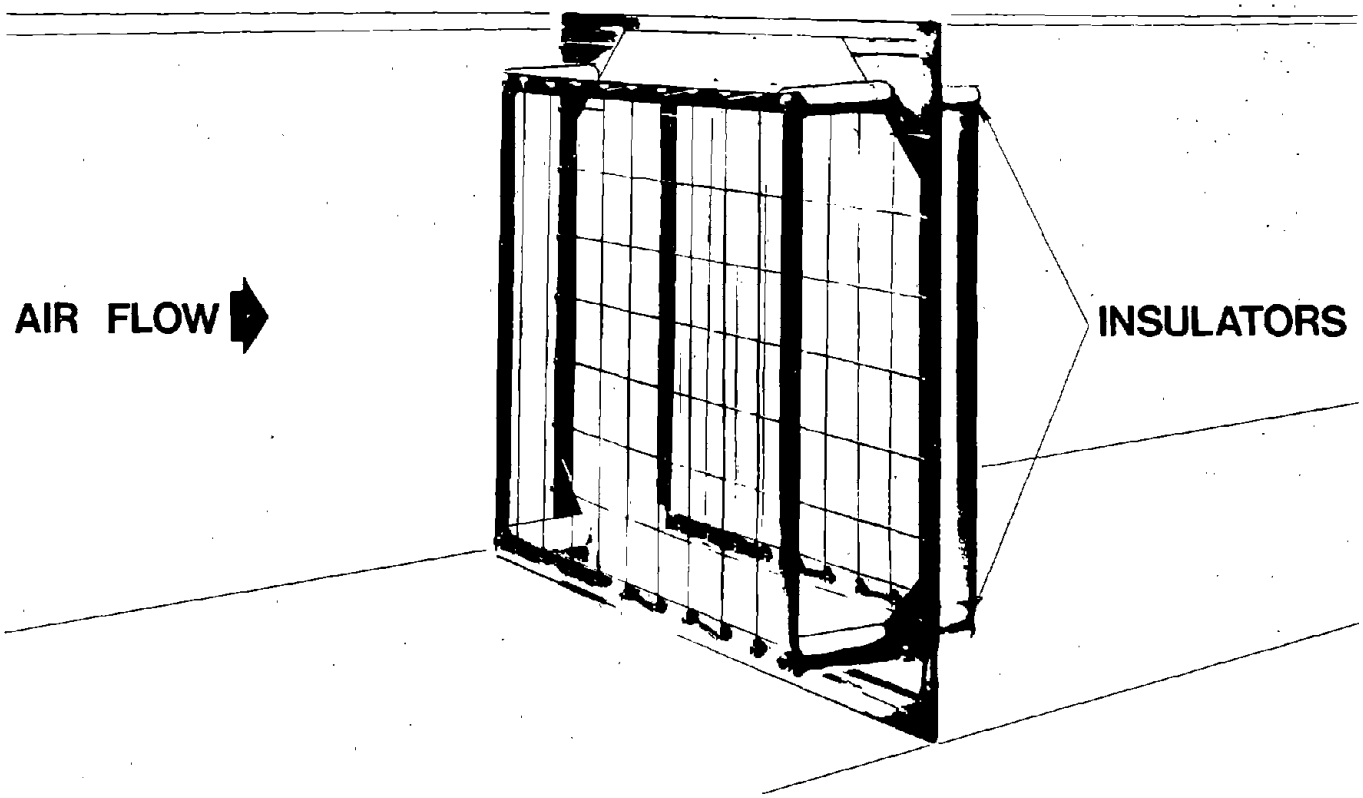

Figure 3 Electric field screens

cantly different at the .001 level, as shown in Table 5. Specifically, at the 15-minute point, the measured respirable mass with the electric field off was 13.6 mg/m³; with the electric field on it was 8.9 mg/m³. At the 30-minute point, the measured respirable mass with the electric field off was 6.8 mg/m³; with the electric field on it was 3.3 mg/m³. The laser light-scattering test yielded similar results, as shown in Table 6.

Discussion

Statistical analyses of these data indicate that passing room air through specific in-duct electric fields substantially reduces the respirable aerosol mass in a room. The mass measurement instrument indicates the electric fields reduce the aerosol mass in the room by approximately half.

EXPERIMENT 2

Since the in-duct fields were effective in reducing room contamination, experiment 2 was designed to determine if an acceleration of coagulation takes place when the in-duct fields are in operation.

Experimental Setup and Method

The testing was carried out in a room 4 m by 11 m by 2.5 m high (13 × 36 × 8 ft). Air entered the room through a pair of slot supply diffusers near the ceiling centerline, passed down through the room, and exited into a duct through a pair of slot return grilles at the bottom of the walls that were parallel to the diffuser slots. In the duct, the air passed sequentially through a smoking device, a 55% ASHRAE-rated filter, a blower, three electric field screens, and then re-entered the room through the supply diffusers. The room air change rate was 10 per hour with 50% recirculation. The air supply was filtered through activated alumina to remove moisture. The temperature ranged about 70°F with a low relative humidity. Comparable results have been obtained with the full range of humidities typically encountered in buildings. The air in the room was purged to the outside between test runs and said runs were separated by at least two days.

The three electric field screens shown in Figure 3 (A, B, and C with A upstream) were installed in the duct. Screens A and C were 53 × 45 cm and screen B was 55 × 51 cm. Screens A and C consisted of vertical bands of 0.33 cm braided wire 4.5 cm apart on centers. The bands on screen B were horizontal and 5.5 cm apart. The screens were spaced 7.6 cm apart. Electric field generators supplied a 700 V pp, 177 kHz signal that was applied to screen B and also a 25 kV DC signal that was applied to screens A and C. The current was less than 3 ma.

The smoke was generated by burning cigarettes in a smoking device in the duct. For a 75-minute period in each run, a mean rate of 1044 mg/min of airborne burned cigarette products was produced. This mean was calculated from the pre-burn weight of the cigarettes burned less the ash and butts remaining from each run. No run deviated more than 7% from this mean.

Two particle-measuring instruments were used concurrently in the experiment. One was a particle monitor, which measured particle concentration and size by light scattering. Particles of 0.5 micron diameter and larger can be detected in concentrations up to 10 million particles/ft³. Particle size range threshold is selectable and includes 0.5 micron and larger, 1.0 micron and larger, and 2.0 microns and larger. The instrument has a sampling flow rate of 0.01 cfm.

The other instrument used was an aerosol particle analyzer, which measures particle concentration and size by mass. It is a 10-stage cascade impactor with quartz crystal microbalance mass monitors in each stage. Two unsealed crystals, one for particle collection and one for temperature sensing, are used in each stage. By use of a crystal pair with the same temperature characteristics, the reference crystal nulls out

any temperature effect on the sensing crystal. The nominal aerodynamic diameters (50% cutoff) for particles of a mass density of 2 g/cm^3 are in microns: 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.5, and 25. The instrument was set for continuous, automatic sampling of the air, with sampling periods of 180 seconds. This instrument provided a printout of the frequency and mass for each stage at the end of each 180-second sampling period throughout each test run. The two instruments were located on horizontal surfaces 45 cm high on opposite sides of the room, 90 cm from the wall.

During each 90-minute test run, there was no smoke introduced into the air for the first 15 minutes. During the next 20 minutes, the smoking of the cigarettes began and the smoke distribution in the room was allowed to stabilize. During the remaining 55 minutes, the smoking was held at an essentially constant rate. Thus, the primary data for the analyses were the last 55 minutes of each experimental run.

A counterbalanced experimental design was used with the electric fields off for days 1 and 4 and on for days 2 and 3.

Results and Discussion

In accordance with a standard experimental design intended to null out any possible trend effects, the days 1 and 4 data (field off) gathered after smoke levels stabilized were combined and the days 2 and 3 data (field on) were combined.

The mean counts of the on vs. off data for each particle size and larger (0.5 micron, 1 micron, 2 microns) are shown in Figure 4. The statistical analysis of these data shows that the mean particle count of size 0.5 micron and larger for the field off condition was 30,013 and for the field on it was 24,882. This difference is statistically significant at the .01 level ($t = 3.63$). The mean particle count of size 1 micron and larger for the field off condition was 5638 and for the field on it was 2653. This difference is significant at the .01 level ($t = 3.53$). The mean particle count of size 2 microns and larger for the field off condition was 2466 and for the field on it was 1217. This difference is significant at the .01 level ($t = 2.99$).

Statistical tests of the cascade impactor data obtained before smoking began (during the first 15 minutes) showed that there were no significant differences between runs in the

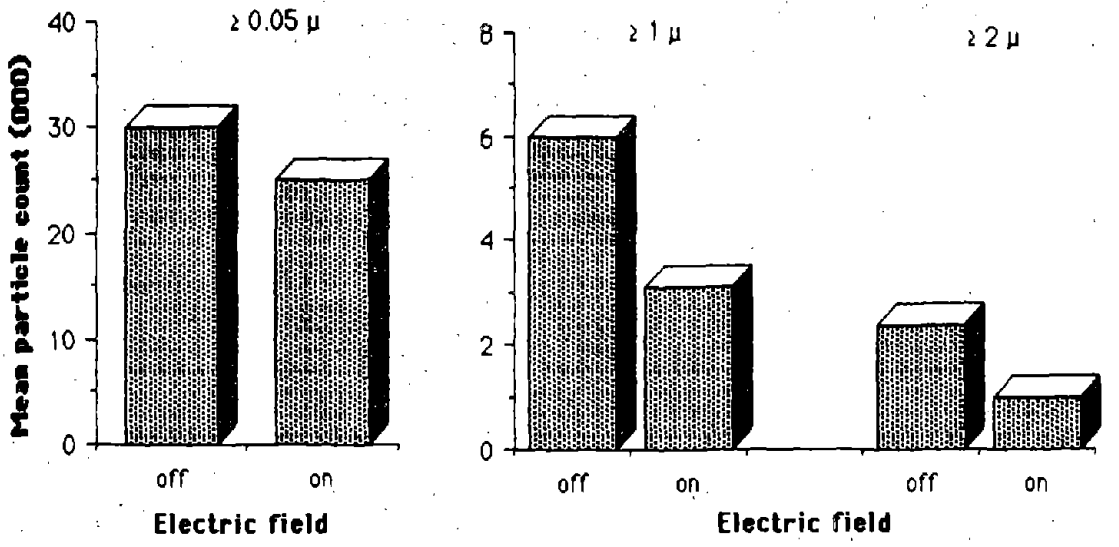

Figure 4 Comparison of mean particle counts with electric field off vs. on

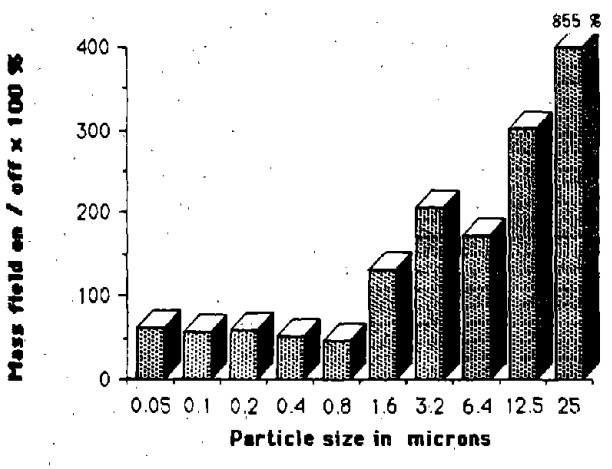

Figure 5 Percent decrement or increment in particle mass from baseline of 100% when the electric field was on. The baseline is the field off data. The difference in mass between on and off conditions at each particle size was statistically significant, except at the 1.6 micron size.

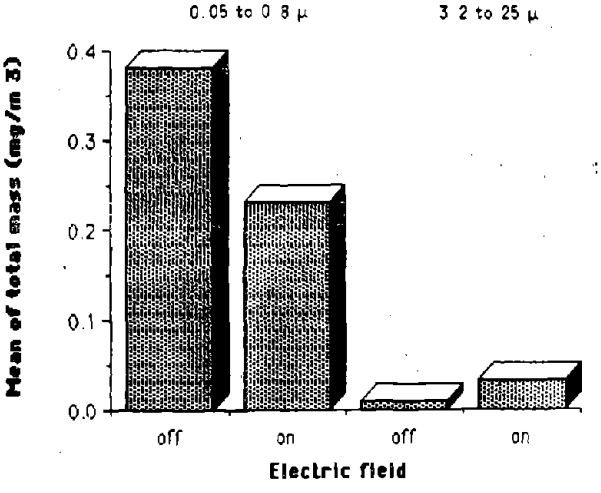

Figure 6 Comparison of mean masses with electric field off vs. on

number of particles at the various sizes. Thus, all testing started from the same pre-smoke baseline. The first objective in analyzing the cascade impactor data was to see if the results from the two instruments were consistent. Since one instrument operates by light scattering and the other operates by mass measurement, one would expect substantial, though not complete, correlation in the results.

The particle monitor measured all particulates in the air 0.5 microns and larger. A comparable set of data from the cascade impactor was obtained by summing the data from the first seven stages of the impactor, which includes all particulates 0.4 microns and larger. The mean mass for the electric field on condition, day 2 and 3 data, was significantly less than that for the off condition, day 1 and 4 data ($t = 3.03$, $p < .005$). Thus, both instruments indicated that the electric field in the duct was significantly decreasing the particulate concentration in the room.

The crystals for two of the ten stages, the 0.05 micron and the 0.1 micron, overloaded during the last 35 minutes of some of the runs. In the following statistical analyses in which data from those two stages are included, the analyses were done without the data obtained from those two crystals during the time they were overloaded. This minor loss of data had no influence on the conclusions drawn.

A statistical analysis using the data from all 10 stages was carried out. The results were comparable to what was found with the seven stages; there were differences and they were significant ($t = 5.02$, $p < .005$).

Statistical analyses were also done stage by stage. These showed that the operation of the in-duct electric field substantially reduced the mass of small particulates in the air and slightly increased the mass of large particulates. This relationship is shown in Figure 5 as percent decrease or increase in mass from the mass determined in the no-electric field condition. The difference between field on vs. off data at each stage was statistically significant except for the 1.6 micron stage data.

Since the 1.6 micron size seemed to be the transition point, it was used as a break point in further analyses. The mean mass for the small particles (0.05 to 0.8 microns) was calculated. For the electric field on condition, it was 0.232 mg/m^3; and for the off condition, it was 0.378 mg/m^3, as shown in Figure 6. Thus, the operation of the electric field reduced the mass of small particles in the room air to 61% of what it was in the field off condition.

The mean mass for the large particles (3.2 to 25. microns) was calculated. For the electric field on condition, it was 0.033 mg/m^3; for the off condition it was 0.009 mg/m^3. Thus, the operation of the electric field increased the mass of the large particles in the air to 367% of what it was in the off condition.

Note that the loss of small particle mass is not balanced by the gain in large particle mass. The gain of 367% in large particle mass in the field on condition accounts for only 6% of the mass lost in small particles. The other 94% of the decrement in small particle mass is going elsewhere. In view of the fact that there is a significant increase in large particles, these data could be interpreted to indicate that this 94% of small particle mass that is unaccounted for is being deposited in the filter. Earlier research shows that it is not plating out in the room (Frey 1986a).

In sum, the statistical analysis of the data indicated that the operation of these specific electric fields in the duct significantly reduced the particle count in the room. The statistical analyses of the cascade impactor data support that conclusion and suggest enhanced coagulation is occurring. The shift in particle size can be interpreted as the operation of the electric field causing the small particles to coalesce into larger particles, which are more readily trapped in the filter (Frey 1985). Thus, there is a means, based on theory and data, for enhancing the effectiveness of filters. Consequently, there are significant implications for controlling contamination and improving human health and comfort. This latter was tested in an extension of this experiment which is described in experiment 3.

EXPERIMENT 3

Experiment Setup and Method

The setup was the same as in the prior experiment except that it was a one-pass system.

Subjects

Forty-eight smokers and forty-eight nonsmokers were asked to rate the degree of odor and also irritation due to cigarette smoke. They were seated in four rows, eight seats to a row. Nonsmokers sat in the first two rows and smokers occupied the two rows behind them. Sixteen smokers and sixteen nonsmokers were tested for each of three air change rates: 5, 7.5, and 10 per hour. Each set of 32 subjects was tested for 1.5 hours for one day with the in-duct electric fields off and again for 1.5 hours at the same time of day with the fields on. The order of the control test vs. the experimental test was counterbalanced across the three air change rate conditions. That is, 5 and 10 air change tests were run with field off on the first day and field on the second day and vice versa with the 7.5 changes tests. Subjects had no knowledge of the test conditions and were simply asked to rate the odor and irritation once every five minutes during each test. Age and sex composition of the groups varied, with the ages ranging from 18 to 59. Every effort was made to have all subjects retested on the second day of an experimental-control series. If all subjects were not able to return, the group was supplemented with additional volunteers so that the number of smokers and nonsmokers was constant. The data from the fill-in subjects were not used.

In the 10 air change test, 28 subjects (11 male, 17 female) were present for both the experimental and control tests. In the 7.5 air change test, 26 subjects (22 male, 4 female) were present for both tests. In the 5 air change test, 29 subjects (14 male, 15 female) were present for both tests. All statistical comparisons were made within the subsets of subjects present for both tests. An effort was made to minimize "demand" characteristics of the situation. Subjects were identified only by seat number, age, and sex, not by name.

A rating scale developed by Yaglou was adapted as the primary measure. It is not ideal, but there is a data base available to use as a reference. Subjects were asked to rate the perceived odor and irritation once every five minutes on a labeled scale of 0 to 5, as shown in Table 7.

A possible limitation of the Yaglou scale was that the labels may have constrained the use of the extreme end of the scale; all labels at 3 and above were termed "objectionable." This mode of labeling may have artificially limited the scale so that raters were reluctant to use these "extreme" ratings. In fact, the data suggest that this did occur to some degree; almost all ratings fell within the range of 0, 1, 2, and 3.

Smokers were instructed to smoke a minimum of three cigarettes over the 1.5-hour test period. Butt counts indicated that the number of cigarettes smoked was relatively constant

TABLE 7

Sensory scale for strength of cigarette smoke odor or for degree of irritation to eyes, nose, and throat (from Yaglou 1955)

Index No.	Description
0	Imperceptible odor or irritation
1	Threshold of odor or irritation perception. Not objectionable.
2	Moderate odor or irritation. Acceptable level.
3	Objectionable odor or irritation. Unpleasant. Regarded with disfavor.
4	Very objectionable. Strong odor or irritation but endurable.
5	Very strong, intolerable odor or irritation. Causes significant discomfort

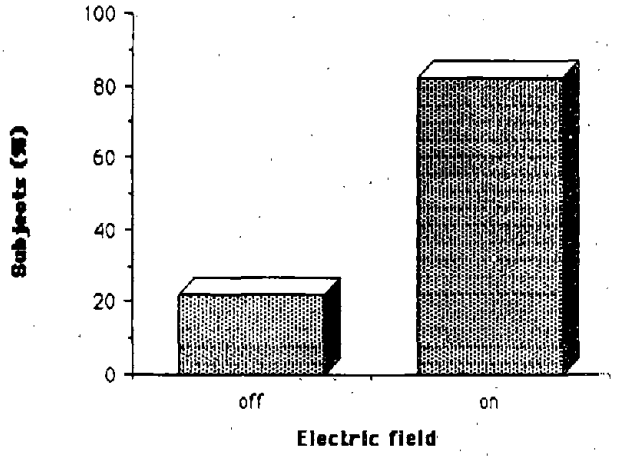

Figure 7 Percentage of subjects who found the room acceptable (irritation measure) when the electric field was on compared to when the field was off. The air change rate was 5 per hour.

from one air change test to the next (mean = 56, SEM = 1.52). The three-cigarette criterion was chosen because an earlier, unrelated, test showed that smokers in a similar situation smoked an average of 2.7 cigarettes per hour. Generally, all subjects lit a cigarette at the beginning of the test. Thereafter, 10-minute counts indicated that an average of about five cigarettes were being smoked at any given time. There was a slight increase in smoking in the last 10 minutes. This may have reflected the subjects' attempt to comply with the quota they had been assigned.

Results

The data were analyzed for the last half hour of each test. This interval was chosen because pilot research indicated that measures of irritability and odor gradually increased during the first hour of exposure and then stabilized. Averages of the six 5-minute ratings made during that interval were calculated for each subject for the field on condition and the field off condition. All statistical comparisons were made within subjects for a given air change condition. Thus, subjects who did not appear for the retest were not included in the analysis. Since Yaglou ratings are on an ordinal scale, the permissive presentation allowed by the mathematical model underlying it is categorization. Categorizations of average ratings of electric field effect by all subjects (smokers and nonsmokers) for both odor and irritation at all air changes are shown in Table 8. These categorizations show consistency across all air change conditions. Average ratings during the

TABLE 8

Average ratings of electric field effect by all subjects, smokers and non-smokers, for both irritation (top half of table) and odor (bottom half of table) at all air change rates

	Irritation		
	air change rate/hr	acceptable	objectionable
field off (smokers)			
	5		*
	7.5		*
	10		*
field on (smokers)			
	5	*	
	7.5	*	
	10	*	
field off (non smokers)			
	5		*
	7.5		*
	10		*
field on (non smokers)			
	5	*	
	7.5	*	
	10	*	

	Odor		
	air change rate/hr	acceptable	objectionable
field off (smokers)			
	5		*
	7.5	*	
	10	*	
field on (smokers)			
	5	*	
	7.5	*	
	10	*	
field off (non smokers)			
	5		*
	7.5		*
	10	*	
field on (non smokers)			
	5		*
	7.5	*	
	10	*	

field on condition are systematically more acceptable than during the field off condition. With the field off, many of the average ratings fall in the unacceptable range even when the air change rate was as high as 10. It is interesting to note that smokers and nonsmokers do not differ markedly in their ratings. These ratings also indicate that odor and irritation are more objectionable for the lower air change rate (5) than for the higher air change rates (7.5 and 10).

Statistical comparisons of field on vs. field off conditions were done for smokers and non-smokers combined for each air change condition. Parametric and non-parametric tests yielded similar results, so for consistency with the rest of the report the parametric test results are presented.

Since prior tests indicated that the in-duct field would reduce perceived irritability due to cigarette smoke, one-tailed matched-pair t-tests were used. Indications were that the irritability measures were somewhat more sensitive and reliable than the odor measures, perhaps because they reflected a more "global" measure. For this reason, final statistical tests were done on irritability measures only. It was found that the level of irritation was significantly less in the field on condition for the 5, 7.5, and 10 air change rates: $t = 3.64$, $p \leq .001$, $t = 1.54$, $p \leq .05$, $t = 3.18$, $p \leq .01$, respectively. How much so can be seen in Figure 7.

Discussion

It is clear that complex in-duct electrical fields, even in a one-pass system such as used here, significantly improve

the perceived air quality in a room. In general, it made acceptable a cigarette smoke environment which would otherwise be unacceptable to people. This is consistent with earlier findings with odorants (Frey 1983, 1986b).

EXPERIMENTS 4 AND 5

Since gaseous contaminants absorb or adsorb on particulates to varying degrees, this line of experimentation was extended to determine the effects of in-duct fields on two gaseous contaminants that are significant to human health and comfort.

Experiment Setup and Method

The gases used were formaldehyde and sulphur dioxide. There were two series of experiments using these gases. In the first series, the initial gas concentrations were set at levels at which the effects on people are just noticeable. In the second series, the initial gas concentrations were set at levels that would be hazardous to people with short exposure. The testing was carried out in the room and with the air-handling system described in Experiment 1.

The upstream electrical field screen installed in the duct was 60 × 60 cm (24 × 24 in) and the downstream one was 50 × 50 cm (20 × 20 in). They were spaced 7.6 cm (3 in) apart. The screens consisted of a .33-cm-wide tinned copper braid. Electric field generators supplied a 25 kV DC signal that was applied to the upstream screen and a 700 V peak-to-peak 177 kHz signal that was applied to the downstream screen. The current was less than 3 ma.

A gas detector tube system was used as the measuring instrument. The detector tubes contain calorimetric reagents adsorbed on fine grain silica gel, activated alumina, or other adsorbing media. The reagents are sensitive to particular gases or vapors and react quantitatively to provide a length-of-stain indication. Each detector tube contains a precise amount of detecting reagent in a constant inner diameter glass tube that is hermetically sealed at both ends. When a measurement was to be taken, the tips were broken off a tube and it was placed in the center of the room and connected to the sampling pump via a hose. The chemical reagent in the detector tube reacted with the sample gas and a color stain developed, starting at the inlet of the detector tube. The gas concentration was measured as the location of the interface of the stained-to-unstained reagent when staining stopped. The calibration curve on most detector tubes is a straight line, and points on the scale are at equal intervals. The calibration scales are printed on the basis of individual production lots. Therefore, possible confounding factors such as the variation of inner tube diameters, precision of tube packing, and the quality and reactivity of each reagent are eliminated. Two evaluators independently read each tube in the first series. One evaluator had no knowledge of the test conditions, so the experiment was double-blind for him. Because of the reliability of the evaluators, as noted in the results, there was only one evaluator in the second series.

The procedure was that the air-handling system was turned on and the air in the test room purged to the outside for 30 minutes. This reduced the concentration of the gas of interest down to normal ambient, as verified by a detector tube measurement at the end of each purge. A gas, such as sulphur dioxide, was then injected into the test room. Sufficient gas was injected to bring the concentration up to approximately the predetermined standard concentration, noted below, that was used in the test. At this point, the gas was turned off and the 60-minute run was started. The gas concentration was measured with detector tubes 5 minutes after injection stopped, 30 minutes into the run, and at the end of the 60-minute run. At the end of each run, the room was purged to baseline concentration and the next run in the test was then begun. There were 12 runs for each gas in each of the two series, six with the fields on and six with them off. The runs were done in an ordered, counterbalanced sequence.

The sulphur dioxide was injected into the center of the room via a hose connected to a cylinder of gas located outside the room. The formaldehyde was injected into the room with an airbrush spraying a 10% formaldehyde solution.

TABLE 9

The initial gas concentrations were set at the level of first noticeable effects in people. The in-duct complex electrical fields reduced, as compared to controls, the concentrations as shown. The significance levels were determined with use of the analysis of variance.

Gas	end of 30 minutes mean percent reduction	signif.	end of 60 minutes mean percent reduction	signif.
HCHO	26	.001	39	.01
SO_2		ns	22	.05

The mean concentration at the 5, 30, and 60 minute points for the above tests were formaldehyde 2.8, 2.5, 1.5 ppm and sulphur dioxide 25.3, 18.7, 14.3 ppm.

The initial gas concentrations in the test results noted below were set at the level hazardous to people when exposed for a short period.

HCHO	39	.001	49	.01
SO_2	13	.01	14	.001

The mean concentration at the 5, 30, and 60 minute points were formaldehyde 4.3, 2.0, 1.3 ppm and sulphur dioxide 49.8, 40.5, 32.9 ppm.

Results

The first question addressed was the reliability of the readings of the detector tubes. Pearson product-moment correlations were computed between the data provided by evaluators 1 and 2. There was near perfect correlation in each set of their readings ($r > .95$). This indicates that they were reliably reading the detector tubes and were doing so without bias.

There was natural decay in gas concentrations over time without the electrical field on. Thus, for clarity of presentation, the data are presented as the percent reduction in the field on condition compared to the control (field off) condition. For testing the significance of the differences between conditions, an analysis of variance was done on the data. The results of the statistical analyses for each of the gases for the first series are shown in the upper part of Table 9. The results of the second series are shown in the lower part.

Discussion

These data on gases extend the finding that passing room air through in-duct complex electrical fields has a significant effect on the concentration of contaminants in a room. The extent and rate of the effect varies as a function of which gas is used, as has been shown in other experiments (Frey 1986c, 1988). The amount of adsorption on particulates or molecular composition are the factors most likely to be involved in this.

CONCLUSIONS

Although filters and charcoal beds effectively remove many room contaminants that are carried to them via the

TABLE 10

Photography Test Sequence

Film Frame Exposure (sec.)	Lens	Aperture
1	1/4	4
2	1/4	5.6
3	1/4	8
4	1/2	5.6
5	1/2	8
6	1/2	11
7	1	8
8	1	11
9	1	16
10	2	5.6
11	2	8
12	2	11
13	4	8
14	4	11
15	4	16
16	10	8
17	10	11
18	10	16
19	1/4	8
20	1/2	8
21	1	8
22	2	8
23	4	8
24	10	8

ducts, a large proportion of the contaminants that are typically found in room air do not reach them. As has been shown (Frey 1986), this is in large part because the motion of contaminants less than one micron in size is determined more by the normal electrical forces in a room rather than by air currents. Thus, a large proportion of the contaminants in a room tend to plateout on people and objects. This results in adverse effects on health and comfort. In this report, a means to enhance the natural process of coagulation so as to more rapidly increase particle size is shown. As a consequence, we have a means to make air currents the dominant force so particulates can be more readily carried to the filters via the ducts. Thus, we have a means to enhance the effectiveness of filters and charcoal beds and in so doing improve air purification. There are also implications for enhancing the control of bacteria which have yet to be tested.

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APPENDIX A

Two commonly used techniques were used to determine if the screens were creating ozone, i.e., time exposure photography and ozone meter measurements. Specifically:

1. If the screens produced ozone via corona, the corona could be detected by time exposure photography. A standardized series of 360 photographs of operating screens were taken.
2. If the screens produced ozone, this ozone could be measured adjacent to the screens when the system is in operation. Four hundred and eighty ozone measurements were made under standard operating conditions.

Details of the photographic procedure and the results are as follows. The camera was used by a professional photographer. Black and white ASA 400 film was used. A series of 360 photographs were taken of screen assemblies installed in a plenum. The screen assemblies were photographed from the downstream side as well as the upstream side using a wide variety of exposure times (from 1/4 to 10 seconds) and lens apertures from f 4 to f 16. A typical test sequence is shown in Table 10.

No corona was found in any of the 360 photographs that were taken and developed by the photographer. The results were consistent roll-to-roll regardless of the exposure time or lens aperture.

Details of the ozone meter procedure and results are as follows.

A monitor that can measure ozone levels down to 0.001 ppm was used. Ozone levels were measured three times a day over five days in seven locations, i.e., outside the building, inside the test room with only the fan running, inside the test room with the electric fields on, inside the plenum, both 15 cm (6 in) upstream and 15 cm (6 in) downstream, and one meter (39 in) downstream of the screens with the fields on and off. Table 11 is a sample of an actual log used in recording ozone levels.

An analysis of variance of the data showed that there were no significant differences in ozone measured when the fields were on vs. off, as is shown in Table 12. The ozone readings recorded were consistent with the Environmental

TABLE 11

Sample of actual logged results of ozone readings (ppm)

Test	outside bldg	inside lab	inside test room	inside plenum (6 in upstream)		inside plenum (6 in downstream)	
1	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2	0.001	0.001	0.001	0.001	0.001	0.001	0.001
3	0.001	0.000	0.000	0.000	0.000	0.000	0.000
4	0.002	0.001	0.001	0.001	0.001	0.001	0.001
5	0.003	0.002	0.002	0.003	0.003	0.003	0.003
6	0.002	0.001	0.001	0.001	0.003	0.001	0.002
7	0.003	0.002	0.002	0.002	0.002	0.002	0.002
8	0.003	0.002	0.002	0.002	0.003	0.002	0.003
9	0.002	0.001	0.001	0.001	0.001	0.001	0.001
10	0.003	0.002	0.002	0.003	0.003	0.003	0.003

Protection Agency's outdoor ozone readings for the area at the times the measurements were made.

TABLE 12

Anova Summary Table

Source	SS	df	MS	F ratio	Signif
A	2.5	3	0.85	0.99	ns
B	0	1	0	0	ns
AB	0.2	3	0.07	0.08	ns
Within	62	72	0.86		

DISCUSSION

Carl Lawson, LRW Engineers Inc., Tampa, FL: Do you feel that the electric-charged field will help with absorption of HCHO, CO_2, and CO?

A.H. Frey, Randomline Inc., Huntingdon Valley, PA: The research with in-duct complex fields shows that they enhance the removal of these chemicals from room air. This research has been published. I will give you the references after the session. The references will also be published in the Proceedings.

Charles J. Weschler, Bell Communications Research, Red Bank, NJ: How do you explain the reported effect of the electrical field on gas phase molecules such as carbon dioxide or sulfur dioxide?

Frey: It is well established in the literature that gas phase molecules absorb and adsorb onto particles to varying extents. Thus, to the extent that the particles coagulate and are then caught in the filter, the absorbed and adsorbed gas phase molecules will also be retained in the filter. It is comparable to the gas molecules adsorbing on charcoal particles and these being caught in the filter.

EFFECT OF HYGROSCOPIC MATERIALS ON INDOOR RELATIVE HUMIDITY AND AIR QUALITY

M.K. West E.C. Hansen

ABSTRACT

One source of moisture-associated air quality problems is the proliferation of microbes on moist hygroscopic bodies within a space. Reduction of ventilation air can elevate material moisture content by disturbing building moisture balance. Methods to accurately predict material moisture content and sorption influence on building moisture balance are needed.

A moisture mass balance model was used to predict the effect of hygroscopic furnishings on indoor relative humidity. The objective was to model moisture mass transport in a structure and predict the magnitude and duration of material sorption. A rigorous moisture balance equation is solved analytically and numerically. A closed form simplification is used, along with material properties previously determined, to calculate relative humidity. Results show that hygroscopic furnishings can change humidity by 15% to 20% for as long as one month. It is concluded that hygroscopic furnishings should be considered when predicting indoor humidity.

INTRODUCTION

Reduction of the quantity of ventilation and infiltration air can change indoor air moisture content. This will occur when a weatherized structure operates with ineffective moisture control equipment—a common practice, especially in residences. A simple moisture mass balance of a structure indicates that the indoor air moisture content depends on the difference between moisture generation, influx, and desorption rate; and moisture removal and absorption rate. By reducing the influx of outdoor air, the removal (or influx) of moisture is reduced and indoor relative humidity increases (or decreases).

Building problems related in some manner to moisture can be grouped into four categories: (1) occupant immune reactions to microbes (including fungi) and their toxins, (2) transmission of infection via airborne viral matter, (3) structural degradation of the building itself, and (4) energy consumption for space air-conditioning.

Occurrence of upper respiratory illness is linked to relative humidity, as both human susceptibility and pathogen virility are influenced by air moisture content (Lester 1948; Lubart 1962). Growth and reproduction rates of fungus and mold increase with relative humidity (Block 1953). Pulmonary uptake of volatile organic compounds may decrease in dry air (Green 1982). Formaldehyde levels may be affected by relative humidity (Kusuda 1983). Relative humidity has an important influence on comfort and personal hygiene (Nevins 1966; Koch et al. 1960). Control of building relative humidity can reduce the occurrence of building-related illness, transmission and susceptibility to airborne pathogens, viability of decay fungi, and affect building energy use.

A problem encountered in attempting to properly control indoor relative humidity is performing an accurate moisture load calculation in order to optimize selection and operation of air-conditioning equipment. Practicable analysis methods for moisture mass transport on par with those of thermal transport are needed. It is unclear whether the influence of hygroscopic materials should be considered in predictions of indoor humidity (Fairey and Kerestecliogiu 1985; Kusuda 1986; Kent 1966; Miller 1984).

The objectives of this work are to determine (1) the magnitude of the effect of hygroscopic furnishings on space air moisture content and (2) for what period of time those effects remain significant.

MODEL

Analysis of moisture transport in buildings begins by considering the moisture gains and losses of the structure. The dynamic balance of moisture gain and loss by the building air determines the relative humidity at any instant. An analysis must consider (1) ventilation and infiltration rates and the difference in moisture content of indoor and outdoor air; (2) internal moisture generation from bathing, cooking, humidifiers, etc.; (3) losses due to condensation and diffusion; and (4) absorption/desorption of moisture by hygroscopic materials within the space. Considering the space boundary to be a control surface, the following mass balance is written:

$$w\frac{dm_s}{dt} = m_o(i+V) - m_s(e+E) + g - c(m_s) - a(m_s,m_s') - d(m_s) \quad (1)$$

and by continuity

$$s = r + V - E \text{ and } E = V + i - e$$

where

a = sorption rate
c = condensation rate
d = diffusion rate through space boundary
E = exhaust airflow from HVAC to outside
e = exfiltration airflow from space to outside
g = generation rate
i = infiltration flow from outside to space
m_m = supply air moisture content
m_o = outside air moisture content
m_s = space air moisture content
r = return airflow from space to HVAC
s = supply airflow from HVAC to space
T_a = outside air temperature
T_s = space air temperature
V = ventilation airflow from outside to HVAC
w = space air volume

Sorption rate and diffusion rate can be positive or negative. For sorption $a = a(m_s,m_s',T_s)$, for condensation $c = c(m_s,T_s,T_a)$, and for diffusion $d = d(m_s,m_o)$. Mechanical humidification and dehumidification are modeled as a portion

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of generation and condensation rates, respectively.

Simplification of Equation 1 is required to obtain an analytical closed-form solution. Three means of simplification will be explored. Each successive simplification produces a more useful relation but lessens the rigor of the analysis, of course. All three simplifications are required to arrive at a readily applicable analytical relation.

The first is to assume condensation, sorption, and diffusion exhibit the polynomial behavior:

$$c(m_s,T_s,T_a) = c_0 + c_1m_s + c_2m_s^2 + c_3m_s^3 + c^*(T_s,T_a) \quad (2a)$$

$$a(m_s,m_s',T_s) = a_0(t) + a_1(t)m_s + a_2(t)m_s^2 + a_3(t)m_s^3 + a^*(T_s) \quad (2b)$$

$$d(m_s,m_o) = d_0 + d_1m_s + d_2m_s^2 + d_3m_s^3 + d^*(m_o) \quad (2c)$$

The second simplification ignores the dependence of sorption on the rate of change of space air moisture content since sorption is only a weak function of this variable. Thus, Equation 2b is reduced to:

$$a(m_s,T_s) = a_0 + + a_1m_s + a_2m_s^2 + a_3m_s^3 + a^*(T_s) \quad (3)$$

The third successive simplification is an assumption of linear behavior of condensation, sorption, and diffusion with respect to space air moisture content. This assumption makes analytical solution uncomplicated, but it is quite severe and limits the rigor of the analysis. Using this treatment, results are only valid for small changes in space air moisture content. The following relations are obtained:

$$c(m_s,T_s,T_a) = c_0 + c_1m_s + c^*(T_s,T_a) \quad (4a)$$

$$a(m_s,T_s) = a_0 + a_1m_s + a^*(T_s) \quad (4b)$$

$$d(m_s,m_o) = d_0 + d_1m_s + d^*(m_o) \quad (4c)$$

The solution of Equation 1 using Equation 2 is begun by substitution and application of the initial conditions

$$at\ t = 0:\ V = E = e = r = s = 0$$

yielding Equation 1 as

$$\frac{dm_s}{dt} = A_0 - A_1m_s - A_2m_s^2 - A_3m_s^3 = F(m_s,t) \quad (5)$$

where

$$A_0 = k_0 - a_0(t) - c_0 - d_0$$
$$A_1 = k_1 + a_1(t) + c_1 + d_1$$
$$A_2 = a_2(t) + c_2 + d_2$$
$$A_3 = a_3(t) + c_3 + d_3$$
$$k_0 = m_o(i+V) + g$$
$$k_1 = e + E + r$$

The solution is had numerically or by means of the transformations

$$m_s(t) = A(t)Z(x) + B(t) \quad t = \int A^2(t)A_3dt$$

giving

$$\frac{dZ}{dx} = Z^3 + P(t)$$

$$where\ P(t) = \frac{1}{A^3(t)A_3}\left[A_0 - \frac{A_1A_2}{3A_3} + \frac{2}{27}\left(\frac{A_2^3}{A_3^2}\right) + \frac{1}{3}\frac{d}{dt}\left(\frac{A_2}{A_3}\right)\right]$$

$$A(t) = exp\ Q(t),\ Q(t) = \int\left(A_1 - \frac{A_2^2}{3A_3}\right)dt,\ B(t) = -\frac{A_2}{3A_3}$$

Employing Equation 3, Equation 1 reduces to the form

$$\frac{dm_s}{dt} = A_0 + A_1m_s + A_2m_s^2 + A_3m_s^3 = G(m_s) \quad (6)$$

thus the roots of $G(m_s) = 0$ are solutions of Equation 6 and the general solution is

$$(m_s-m_1)^a(m_s-m_2)^b(m_s-m_3)^c = Kexp(A_3t)$$

where m_1, m_2, and m_3 are roots of $G(ms) = 0$; a, b, and c are fixed constants; and K is an arbitrary constant.

Making use of Equation 4 results in $A_2 = A_3 = 0$ and Equation 1 is reduced to

$$\frac{dm_s}{dt} = A_0 + A_1m_s \quad (7)$$

Substitution yields

$$w\frac{dm_s}{dt} = m_o(i+V) - m_s(e+E) + g-c-a-d \quad (8)$$

and for the initial condition

$$m_s(0) = m_oi - m_se - a - d$$

the general solution is

$$m_s(t) = \alpha\ exp(-Mt) + \frac{N}{M}$$

where

$$wM = e + E$$
$$wN = m_o(i+V) + g - c - a - d$$
$$\alpha = \text{a constant of integration.}$$

A further substitution yields the form

$$m_s(t) = Dexp\left(-\frac{e+E}{w}t\right) + \left(\frac{m_o(i+V)+g-c-a-d}{e+E}\right) \quad (9)$$

$$where\ D = \frac{1}{e}m_oi(e-1) - (a+d)(e+1) - m_se^2$$

As t becomes infinite the steady-state moisture content is described by

$$m_s = \frac{m_o(i+V) + g-c-a-d}{e + E} \quad (10)$$

APPLICATION

A control volume analysis of building air moisture content was performed using the above equations, the material properties previously evaluated, and the following equations:

$$a = \frac{dU}{dt} = \frac{qm}{pR} \text{ for } t < t_{cr} \quad (11)$$

$$U = U_A\ exp(-kt) + U_f \text{ for } t > t_{cr} \quad (12)$$

where $U = u \cdot m$; u is the material moisture content; m is the mass of the hygroscopic body; t is time; p is density; R is volume-to-surface ratio; and U_A, U_f, q, and k are constants experimentally determined previously (West and Hansen 1989).

The analysis was performed for a model typical of a 2000 ft² home and a family of four. The descriptive parameters of the model are given in Table 1. The effect of hygroscopic furnishings was evaluated for the following process. For times less than zero: (1) space air conditions are 78°F (25.6°C), 85% RH; (2) the hygroscopic materials are at equilibrium; (3) $Q_s = Q_l = 0$; and (4) space air can mix with outdoor air (win-

TABLE 1A

Basic values used in moisture balance analysis, I-P units.

Variable	Value t > 0
nfiltration rate	0.5 ach
nfiltration, i	8000 ft^3/hr
generation rate, g	1.2 lb_w/hr
AC condensation rate, C	4.0 lb_w/hr
outdoor temperature, T_a	80 F
space temperature, T_s	75 F
outdoor humidity, rh_a	65%
inal indoor humidity, rh_f	48%
outdoor air moisture, m_o	0.014 lb_w/lb_a
inal indoor moisture, m_f	0.009 lb_w/lb_a
sensible cooling, Q_s	11,780 Btu/hr
atent cooling, Q_l	3,865 Btu/hr
sensible infiltration, I_s	726 Btu/hr
atent infiltration, I_l	2,581 Btu/hr
transmural load, L	3,750 Btu/hr
solar load, S	5,200 Btu/hr
sensible generation, G	1,200 Btu/hr
sensible occupancy, O	900 Btu/hr

TABLE 1B

Basic values used in moisture balance analysis, SI units.

Variable	Value t > 0
infiltration rate	0.5 ach
infiltration, i	62.9 L/s
generation rate, g	0.54 kg_w/hr
AC condensation rate, c	1.81 kg_w/hr
outdoor temperature, T_a	26.7°C
space temperature, T_s	23.9°C
outdoor humidity, rh_a	65%
final indoor humidity, rh_f	48%
outdoor air moisture, m_o	0.014 kg_w/kg_a
final indoor moisture, m_f	0.009 kg_w/kg_a
sensible cooling, Q_s	3.452 kW
latent cooling, Q_l	1.132 kW
sensible infiltration, I_s	0.213 kW
latent infiltration, I_l	0.756 kW
transmural load, L	1.099 kW
solar load, S	1.5 kW
sensible generation, G	0.35 kW
sensible occupancy, O	0.26 kW

TABLE 2A

Furnishing parameters used in moisture balance analysis, I-P units.

tem	1/R[1/ft]	M [lb]	p[lb/ft^3]	a[lb/hr]
bedding	2.7	160	3.1	0.077
clothes				
cotton	3.1	120	12.4	0.016
polyester	3.1	50	18.5	0.001
cushions				
cotton	4.3	14	1.9	0.017
urethane	3.1	48	2.5	0.006
wood	4.0	620	30.0	0.017
carpet	32.0	615	13.2	1.040
padding	48.0	375	11.8	0.488

TABLE 2B

Furnishing parameters used in moisture balance analysis, SI units.

Item	1/R[1/m]	M [kg]	p[kg/m^3]	a[kg/hr]
bedding	8.6	72.6	49.6	0.0349
clothes				
cotton	10	54.4	199	0.0073
polyester	10	22.7	296	0.0005
cushions				
cotton	14	6.35	30.4	0.0077
urethane	10	21.8	40.0	0.0027
wood	13	280	480	0.0077
carpet	100	280	211	0.472
padding	160	170	189	0.221

lows open). At time zero: (1) the air mixing is terminated windows closed), and (2) Q_s and Q_l take on the values listed n Table 1 (AC operational). To force a conservative predic- ion of the length of time hygroscopic furnishings affect in- door humidity, the hygroscopic materials experience rh_f for ll $t > 0$. The furnishing materials used in the analysis are described in Table 2.

To characterize the effect of the furnishings on indoor humidity, the following parameters were calculated: (1) the constant rate period desorption rate, a_{cr}; (2) the desorption rate after 99% of the sample's total desorbed moisture has transferred to the space, a_{99}; (3) the time required to reach the end of the constant rate period, t_{cr}; (4) the time required for the desorption rate to reach an ineffectual level, t_a; and (5) the time required for 99% of the sample's total desorbed moisture to enter the space, t_{99}. The ineffectual desorption rate is defined as the rate which does not affect indoor humidity by more than 1%, a_a = 0.08 lb/h (0.035 kg/h) total for all materials combined. For each material individually, the value of a_a depends upon the number and intensity of other materials still desorbing. A negligible desorption rate of a_a = 0.01 lb/h (0.005 kg/h) is assumed for each material. The calculated parameters are given in Table 3. Values for a_{cr} are equal to a in Table 2.

DISCUSSION

The findings differ by as much as two orders of magnitude among materials. This correlates well with results reported in the literature, which show hygroscopic effects lasting from a few hours (Miller 1984) to many months (Kent 1966).

The carpet had the highest initial (1.040 lb/h, 0.4712 kg/h) and 99% (0.035 lb/h, 0.0159 kg/h) desorption rates. The rates reported for the carpet are effective rates since a portion of its available drying intensity was used by the underlying padding; padding desorption into the space must transpire through the carpet. The padding's initial and 99% desorption rates were roughly one-half the carpet's. The polyester clothing had a negligible desorption rate.

The wood had by far the largest time parameter values. It took approximately 100 days to reach U_{cr}, 122 days for its desorption rate to reach 0.01 lb/h (0.005 kg/h), and 246 days for 99% of total desorbed moisture to enter the space. In contrast, the time parameter values for the cotton clothing were approximately 8 days to reach U_{cr}, 9 days for its desorption rate to become 0.01 lb/h (0.005 kg/h), and 19 days for 99% desorption. The quickest response was displayed by the carpet; it reached U_{cr} in 7 hours, 0.01 lb/h (0.005 kg/h) desorption rate in 21.2 hours, and 99% desorption in 17.3 hours.

The indoor relative humidity for the model was increased from 48% to 64% by hygroscopic desorption. As desorption rates fell, relative humidity dropped to within 1% of its final equilibrium value after 30 days. The principal contributors to desorbtion as the model proceeded are listed in Table 4. After 2 days, wood became the principal contributor to desorbed air moisture within the space; it was responsible for 60% of

TABLE 3A

Parameters characterizing sorbtion effects on air moisture content, I-P units.

Item	a_{99}[lb/hr]	t_{cr}[hr]	t_s[hr]	t_{99}[hr]
bedding	0.00257	22.7	42.6	55.8
clothes				
cotton	0.00053	188.1	226.0	462.4
polyester	0.00002	311.1	0.0	764.6
cushions				
cotton	0.00054	17.3	21.2	42.9
urethane	0.00022	52.3	0.0	126.6
wood	0.00055	2405.5	2921.4	5909.1
carpet	0.01823	7.0	21.0	17.3
padding	0.01627	13.2	35.2	32.4

TABLE 3B

Parameters characterizing sorbtion effects on air moisture content, SI units.

Item	a_{99}[kg/hr]	t_{cr}[hr]	t_s[hr]	t_{99}[hr]
bedding	0.00116	22.7	42.6	55.8
clothes				
cotton	0.00024	188.1	226.0	462.4
polyester	0.00001	311.1	0.0	764.6
cushions				
cotton	0.00024	17.3	21.2	42.9
urethane	0.00010	52.3	0.0	126.6
wood	0.00025	2405.5	2921.4	5909.1
carpet	0.00827	7.0	21.0	17.3
padding	0.00738	13.2	35.2	32.4

TABLE 4

Materials having the dominant effect on indoor relative humidity after time t and their responsible fraction of humidity increase over 48%.

t[hr]	rh_s[%]	materials (fraction)
0	64	carpet (.63), padding (.29), bedding (.04)
48	52	wood (.60), cotton (.34), cushions (.03)
120	50	wood (.79), cotton (.20), polyester (.03)
720	49	wood (1.00)
920	48	—

all desorbed airborne moisture. After 30 days, wood was the only material with a significant desorption rate. After 38 days, the wood desorption rate dropped to 0.07 lb/h (0.032 kg/h) and it no longer affected the indoor relative humidity of the model.

CONCLUSIONS

The model shows that hygroscopic bodies can have a significant effect on air moisture content. The period of the effect depends on the body's surface-to-volume ratio and density as well as its hygroscopic properties. Indoor relative humidity can be changed on the order of 15% to 20% by a combination of hygroscopic bodies typical of residential furnishings. This change in relative humidity is supported by materials having both short- and long-term effects on space air moisture content.

Of the materials tested, the nylon pile jute-backed carpet and urethane rubber composite padding increase relative humidity the most in a simple model analysis. However, their effects last only two days. Sorption by wood causes an appreciably weaker but longer-lasting deviation in indoor relative humidity. The effects of wood can last on the order of one month. Hygroscopic materials should be considered when predicting indoor relative humidity.

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DETERMINATION OF MATERIAL HYGROSCOPIC PROPERTIES THAT AFFECT INDOOR AIR QUALITY

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ABSTRACT

Moisture-associated air quality problems frequently stem from the proliferation of microbes on hygroscopic bodies within a space. Airborne microbe concentrations can be diminished by regulating material moisture content. Knowledge of material hygroscopic behavior is necessary for this strategy to be effective. Hygroscopic materials recurrently associated with moisture-related building problems were tested. The objective was to determine material moisture content as a function of relative humidity, temperature, and time. Samples were exposed to controlled conditions in an environmental chamber and massed in situ to determine moisture content based on dry mass.

Results show that samples of fiberglass duct lining, polyester filter material (both from a veterinary hospital known to have an air quality problem), cotton cloth, and jute-backed nylon carpet can absorb sufficient moisture to support microbial growth. The experimental system used determined material moisture content to within 0.001 [moisture mass]/[dry sample mass] and sorption rate to within 0.01 lb/h (0.005 kg/h). It is concluded that fiberglass duct lining is unsafe in a microbial context unless organic materials are precluded from the HVAC system.

INTRODUCTION

In buildings, moisture-associated air quality problems commonly stem from the proliferation of microbes on moist hygroscopic surfaces within the HVAC system. In residences, fungus is more commonly found on carpeting and furnishings. Fungus growth can be prevented by keeping these materials dry through the use of controlled humidity. The most beneficial humidity setpoint will maintain a safe moisture content of less than 0.10 lb/lb (Block 1953, 1987) in fungus-susceptible materials. It will also prevent condensation, maximize comfort, minimize energy consumption, and may inhibit infectious microbial transmission.

Problems encountered in attempting to properly control indoor relative humidity are (1) performing an accurate moisture load calculation for proper selection and operation of equipment, and (2) selection of the most beneficial indoor relative humidity setpoint. A useful moisture load analysis requires accurate knowledge of the hygroscopic behavior of the structure so that sorption processes and the moisture content of potentially fungus-supporting materials can be predicted. Researchers involved with indoor humidity problems have stated or shown that a lack of material hygroscopic property data is a major problem in their work (Fairey and Kerestecioglu 1985; Kerestecioglu 1986; Kusuda 1983; Miller 1984).

The sorption behavior of hygroscopic materials found in the building environment is not adequately defined to predict material moisture content or indoor relative humidity. Available hygroscopic property data do not satisfy the rigorous models being developed by researchers.

TABLE 1

Samples tested to determine hygroscopic behavior in this study (A, B, __ , C-Clean, D-Dirty).

#	Sample
	Fiberglass
1C	clean unused
1D	sample from VMTH[a] duct lining
	Polyester filter material
2C	low efficiency (e = 20%), clean
2D	low efficiency from VPFQ[b]
3C	medium efficiency (e = 35%), clean
3D	medium efficiency from VMTH[a] HVAC intake
	Pressed paper ceiling tile
	clean unused
4A	front 0.055 in. section
4C	center 0.070 in. section
4B	back 0.070 in. section
	sample from VMTH[a]
4D	front 0.110 in. section
5	Urethane foam, fine cell
6	Carpet, 100% nylon, jute backed 60 oz/sq yd
7	Carpet pad, rubber-urethane composite 35 oz/sq yd
8	Shirt, 100% cotton
9	Shirt, 90% polyester — 10% cotton

a — veterinary medicine teaching hospital
b — apartment complex rental office

EXPERIMENT

The main experimental system consisted of an environmental chamber, a microprocessor-based digital process controller, and an electronic balance. The chamber was instrumented with two 24-gauge copper-constantan thermocouples (one each for dry- and wet-bulb) and two NBS specification 150 mercury-in-glass thermometers (±0.1°C).

The selected sample materials (Table 1) are linked to some aspect of moisture-related building problems. Samples of fiberglass duct lining and polyester filter material from the intake of a veterinary medical teaching hospital's (VMTH) HVAC system were tested. This building was known to have had an air quality problem. Filter samples from an apartment rental office (VPFQ) were also tested. Wood was not tested because an adequate body of data exists in the literature. The pressed paper ceiling tiles were sectioned because of sample non-homogeneity, and also because the front and back of the tiles may be exposed to different ambient conditions when installed.

Tests were performed to accurately determine equilibrium moisture content (u_e) as a function of relative humidity and temperature, and to approximately determine sorption time constant. Tests exposed the samples to known stable environmental conditions. Material moisture content was determined by massing the sample in situ as the test proceeded. Moisture content is defined as the ratio of moisture mass to dry solid mass. The sample is "dry" when it is free from water

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TABLE 2A

Important parameters of the samples tested, I-P units.

Sample	error in u_e $w(u_e)$ ± [lb/lb]	sample mass m [lb_m] × E3	error in m w(m) ± [g] × E3	density p [lb/ft^3]	surface/ volume 1/R [1/ft]
1C fiberglass	0.001	29.41	0.02	2.43	240
1D VMTH fiber	0.004	8.00	0.02	3.62	79.1
2C low poly	0.002	35.56	0.04	0.50	42.5
2D VPFQ poly	0.002	41.42	0.04	0.59	42.5
3C med poly	0.005	6.59	0.02	0.60	35.1
3D VMTH poly	0.003	12.85	0.02	0.76	32.9
4A tile front	0.001	23.35	0.02	21.0	436
4C tile center	0.001	49.54	0.02	13.7	348
4B tile back	0.002	80.7	0.1	19.4	348
4D tile VMTH	0.001	122.4	0.1	21.4	218
5 urethane	0.002	15.96	0.02	1.30	62.2
6 carpet	0.001	560.0	0.4	13.2	68.4
7 padding	0.001	582.5	0.4	11.8	97.4
8 100% cot	0.001	313.7	0.2	12.4	300
9 90% poly	0.001	357.8	0.2	18.5	400

TABLE 2B

Important parameters of the samples tested, SI units.

Sample	error in u_e $w(u_e)$ ± [kg/kg]	sample mass m [g]	error in m w(m) ± [g]	density p [kg/m^3]	surface/ volume 1/R [1/m]
1C fiberglass	0.001	13.34	0.01	38.9	787
1D VMTH fiber	0.004	3.63	0.01	58.0	260
2C low poly	0.002	16.13	0.02	8.0	139
2D VPFQ poly	0.002	18.79	0.02	9.5	139
3C med poly	0.005	2.99	0.01	9.6	115
3D VMTH poly	0.003	5.83	0.01	12.2	107
4A tile front	0.001	10.59	0.01	336	1430
4C tile center	0.001	22.47	0.01	219	1140
4B tile back	0.002	36.61	0.05	311	1140
4D tile VMTH	0.001	55.54	0.05	343	715
5 urethane	0.002	7.24	0.01	20.8	204
6 carpet	0.001	254.0	0.2	211	224
7 padding	0.001	264.2	0.2	189	320
8 100% cot	0.001	142.3	0.1	199	980
9 90% poly	0.001	162.3	0.1	296	1300

retained in capillaries, in solution, on fiber or cell walls, or by physical adhesion to solid surfaces; not chemically bound water (Luikov 1966). Sample dry mass was determined first so that volatile substances were driven off. Sorption hysteresis of the shirts and the capillary diffusion behavior of fiberglass were also investigated.

THEORETICAL APPROACH

Physical absorption occurs at the solid-vapor interface between the moisture in contact with the solid and airborne water vapor (Harter 1963). This process occurs spontaneously without the addition of energy (Bullock and Threlkeld 1986). The moisture absorbed on the solid is bound to it by capillary attraction; this force causes its vapor pressure to be lower than the vapor pressure of free water at the same temperature. At equilibrium, the vapor pressure of the absorbed water is equal to the vapor pressure of the surrounding air, which is proportional to relative humidity and temperature. The surface tension of the absorbed moisture exerts a force on vapor molecules at the solid-vapor interface, tending to increase their vapor pressure so that condensation occurs at the surface, even though the bulk vapor pressure of the surrounding air may be well below the vapor pressure of free water (Carrier Corp. 1929; Harter 1963). In a capillary-porous body the surface tension force, and thus absorption capability, is inversely proportional to capillary diameter (Luikov 1966). Thus, sorption is a highly material-dependent phenomenon.

The heat and mass transfer occurring at the surface of the body is modeled here as a low-intensity drying process. The conditions considered are drying at constant temperature, humidity, and pressure. This is a quasi-stationary heat and mass transfer process described by the following expressions for the initial constant rate drying period (Luikov 1966):

$$\frac{du}{dt} = \frac{q}{pR} \tag{1}$$

where

q = drying intensity [$lb_m/ft^2 \cdot h$], [$kg/m^2 \cdot s$]
R = volume to surface ratio [ft^3/ft^2], [m^3/m^2]
p = body density [lb_m/ft^3], [kg/m^3]

The drying intensity is equal to the density of moisture flow at the surface of the body. The constant drying process as described by Equation 1 is no longer applicable when a certain critical moisture content, U_{cr} (critical mean volumetric

TABLE 3

Maximum observed equilibrium moisture content of samples tested (listed by u_e, [lb/lb] = [kg/kg]).

Sample	u_e	rh [%]	T[F]	T[C]
1D VMTH fiberglass	0.540	99.1	71.4	21.9
3D VMTH polyester	0.402	99.0	63.9	17.7
8 100% cotton	0.137	99.3	71.9	22.2
6 carpet	0.100	94.0	119.2	48.4
3C medium polyester	0.093	96.0	119.6	48.7
2D VPFQ polyester	0.080	99.3	67.4	19.7
4D VMTH tile	0.060	99.3	67.4	19.7
5 urethane foam	0.052	99.3	67.4	19.7
4A tile front	0.050	99.3	67.4	19.7
4B tile back	0.045	99.3	67.4	19.7
4C tile center	0.044	99.3	67.4	19.7
2C low polyester	0.040	99.3	67.4	19.7
7 rubber-urethane	0.038	94.0	119.2	48.4
1C fiberglass	0.035	99.0	64.4	18.0
9 90% polyester	0.013	99.3	71.9	22.2

TABLE 4

Observed moisture content of samples at typical occupied space condition (listed by u_e, [lb/lb] = [kg/kg]).

Sample	u_e	rh [%]	T[F]	T[C]
3D VMTH polyester	0.081	76.4	68.8	20.4
8 100% cotton	0.057	65.0	69.1	20.6
6 carpet	0.024	54.2	66.7	19.3
1D VMTH fiberglass	0.023	74.7	69.3	20.7
4C tile center	0.017	54.2	66.7	19.3
4B tile back	0.017	54.2	66.7	19.3
7 rubber urethane	0.017	54.2	67.4	19.7
2D VPFQ polyester	0.016	54.2	66.7	19.3
4D VMTH tile	0.015	54.2	66.7	19.3
3C medium polyester	0.014	54.2	66.7	19.3
2C low polyester	0.012	54.2	66.7	19.3
5 urethane foam	0.012	54.2	66.7	19.3
4A tile front	0.011	54.2	66.7	19.3
9 90% polyester	0.006	65.0	69.1	20.6
1C fiberglass	0.005	65.0	70.0	21.1

TABLE 5A

Experimentally determined drying intensity, I-P units.

Sample	$q \times 10^4$ [lb/ft² · hr]	$w_q \times 10^4 \pm$ [lb/ft² · hr]
VMTH fiberglass	29.6	0.03
carpet	10.2	0.05
VMTH polyester	6.170	0.004
VMTH tile	5.52	0.02
100% cotton	5.511	0.006
rubber-urethane	3.175	0.003
fiberglass	2.355	0.002
tile front	2.345	0.002
medium polyester	2.266	0.002
tile back	1.953	0.009
tile center	1.329	0.002
urethane foam	1.045	0.001
VPFQ polyester	1.103	0.004
90% polyester	0.540	0.001
low polyester	0.414	0.002

TABLE 5B

Experimentally determined drying intensity, SI units.

Sample	$q \times 10^3$ [kg/m² · hr]	$w_q \times 10^3 \pm$ [kg/m² · hr]
VMTH fiberglass	131.7	0.1
carpet	45.7	0.2
VMTH polyester	27.44	0.02
VMTH tile	24.54	0.07
100% cotton	24.51	0.03
rubber-urethane	14.12	0.02
fiberglass	10.47	0.01
tile front	10.43	0.01
medium polyester	10.08	0.01
tile back	8.68	0.04
tile center	5.911	0.009
urethane foam	4.647	0.004
VPFQ polyester	4.91	0.02
90% polyester	2.402	0.004
low polyester	1.841	0.009

moisture content), and u_{cr} (critical surface moisture content) are reached (Luikov 1966). u_{cr} and the time required to reach equilibrium, t_{cr}, depend on the volume-to-surface ratio of the body:

$$\text{if } R \text{ is large} \quad \frac{du}{dt} << 1$$

$$\text{if } R \text{ is very large } \frac{d^2u}{dt^2} < 0 \text{ and } u_{cr} > u_{initial}$$

The falling rate drying period, $t > t_{cr}$, is adequately described by an exponential relationship.

$$u = A\ exp(-kt) + B \qquad (2)$$

where

A, B, and k are experimentally determined constants, u is moisture content [mass H_2O]/[mass solid], and t is time [h].

RESULTS

Of the samples tested, only the used fiberglass duct lining from VMTH, the used polyester filter material from VMTH, and the 100% cotton shirt exceeded the critical 0.10 lb/lb moisture content necessary for microbial survival. The jute-backed 100% nylon carpet sample was found to have an equilibrium moisture content of 0.100 lb/lb at 120°F (48.9°C) and 99.3% RH.

The duct from which the VMTH fiberglass and filter samples were taken brought in outdoor air from an area near covered outdoor dog pens. Microscope examination (60x) of the used fiberglass and filter samples revealed soil particles and bits of dried leaves and grass. A light micrograph (30x) of the latex-covered jute carpet backing showed that the latex is non-uniform and is an ineffective moisture barrier. Results are summarized in Tables 2, 3, 4, and 5.

An initially dry, clean fiberglass sample immersed to a depth of 0.75 in (2 cm) showed undetectable capillary diffusion at 30×. It was observed that liquid water did not rise into the fiberglass over a period of 18 days. However, when the sample was initially wet to a height of 2 in (5 cm) and then immersed to 0.5 in (1 cm), the 2 in (5 cm) wetted area was maintained over a 10-day test period at 65% RH, 70°F (21°C). Upon removal from the water, the sample dried to 0.005 lb/lb moisture content in 7 hours at 65% RH, 70°F (21°C).

The behavior of the 100% cotton and 90% polyester samples after wetting to ue = 0.62 lb/lb was also investigated. Equilibrium for both samples was reached in 42 hours. Neither sample experienced hysteresis due to the imposed high initial moisture content.

DISCUSSION

Used (soiled) samples consistently had a higher moisture content than the unused member of a used-unused sample pair. Calculations show that the deposited material in the

VPFQ polyester filter material had an effective moisture content of 0.32 lb/lb at 99.3% RH, 67.4°F (19.7°C). This deposited material is responsible for 50% of the moisture absorbed by the filter at these conditions. The VMTH fiberglass sample moisture content was from 10 to 40 times greater than that of the clean sample at the same conditions. This trend was also evident in the tile samples but to a lesser degree.

Results indicate that cotton and polyester will not have a higher equilibrium moisture content after being wet and then allowed to dry at room conditions than if they are completely dried first before being allowed to come to equilibrium at room conditions.

Fiberglass behaves hydrophobically when at low moisture content. At high moisture content, the water retained on and between the fibers attracts water with sufficient force to replace water lost to evaporation at room conditions. This means that dry fiberglass duct lining in contact with liquid water (for example, a condensate drip pan) will remain dry above the water line, but any section of lining that becomes wet will remain wet as long as part of it remains in contact with liquid water.

The equilibrium moisture contents and drying intensities determined can be directly applied to a building moisture mass balance model in order to predict indoor relative humidity and material moisture content (West and Hansen 1989). Data for additional materials are needed for a complete analysis.

Although the experimental design is simple, the need for precise control of environmental conditions over long test times (up to 16 hours per data point) results in a time-absorbing and delicate procedure. The use of automatic controls and data acquisition is recommended.

CONCLUSIONS

1. Clean fiberglass will not absorb sufficient airborne moisture to support microbial growth. Results show that its maximum hygroscopic moisture content is 0.052 lb/lb at 99.9% RH, 64.4°F (18.0°C). This is well below the required 0.10 lb/lb for growth reported necessary by Block (1953, 1987).
2. Cotton cloth can absorb sufficient moisture from the air to support microbial growth. Results show that an equilibrium moisture content of 0.10 lb/lb is attained at 92% RH, 72°F (22°C).
3. Organic materials attached to fiber strands in microbially contaminated polyester filter material and fiberglass can increase hygroscopicity 2 to 10 times that of clean materials. Results show this increase is enough to allow microbial growth in relative humidities greater than 90% in the material as a whole. Additionally, the organic matter itself appears to absorb sufficient moisture to support microbial growth at relative humidities greater than 60%.
4. Clean fiberglass does not absorb a measurable amount of liquid water by capillary diffusion when initially dry. However, when initially wet, capillary diffusion can proceed at a rate adequate to maintain maximum wetability at 60% RH, 70°F (21°C).
5. Cotton and polyester clothing material do not exhibit the degree of sorption hysteresis necessary to maintain higher than 0.10 lb/lb moisture content at 70% RH, 68°F (20°C). The sample materials can be safely dried indoors within 42 hours from a moist condition (u_e = 0.62 lb/lb).
6. The proliferation of microbes in the HVAC fiberglass duct lining sample obtained from a veterinary medical teaching hospital (which is known to have an air quality problem) exists due to two major factors: i) deposits of fine soil, parts of dried leaves and grass, and microbial matter on the fiberglass increases its ability to absorb moisture from the air tenfold over clean fiberglass; and ii) standing water in condensate drip pans maintains high lining moisture content by capillary diffusion.
7. Fiberglass duct lining is not a safe material to use inside HVAC system components, unless (i) a high-efficiency filter is installed at all air intakes to prevent buildup of organic materials, and (ii) the fiberglass does not contact liquid water. The conditions are easily met with minimal attention in the HVAC system design phase. If they are not maintained, even temporarily, microbial habitability will increase due to increased moisture retention. Remedial measures are very costly in terms of both economics and health. Although "drying out" of contaminated ductwork may kill or deactivate fungi, the residual organic material provides not only substrate for renewed growth, but moisture as well.
8. The experimental apparatus and procedure used in this work are ample for precise and accurate determinations of hygroscopic properties as applied to buildings and residences. Material moisture content can be determined to within 0.001 [moisture mass]/[dry sample mass] and sorption rate to within 0.01 lb_m/h (0.005 kg/h) over the range 20% to 100% RH (±2.5%) and 45°F (7°C) to 120°F (50°C), (±1°F, ±0.5°C).

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DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: Did you notice any reaction with duct liners or fiberglass duct that was moisture-laden after it was exposed to heat?

M.K. West, University of Florida, Gainesville, FL: No. The liner was exposed to 250°F, 5% RH before any moisture-laden heat exposure was maintained. This was done to determine dry mass and to drive off VOCs. Exposure to 120°F, 80+% RH lasted only several hours. Apparently this procedure limited an increased growth reaction since none was noticed. However, the focus of the observations made was the materials themselves and not reactions—thus a subtle reaction may have escaped observation.

Case Studies

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WHAT ARE TYPICAL CONCENTRATIONS OF FUNGI, TOTAL VOLATILE ORGANIC COMPOUNDS, AND NITROGEN DIOXIDE IN AN OFFICE ENVIRONMENT?

P.R. Morey, Ph.D. *ASHRAE Member* **B.A. Jenkins**

ABSTRACT

Air sampling was carried out for mesophilic fungi, total volatile organic compounds (TVOC), and nitrogen dioxide (NO_2) in buildings where occupants reported the occurrence of widespread annoyance and discomfort complaints on at least one floor or building zone. Our objective was to compare air contaminant concentrations found in these buildings with outdoor "reference" contaminant levels.

In most buildings the concentrations of fungi collected during quiescent sampling indoors were 10% to 25% of those found in the outdoor air. In a few buildings elevated levels of fungi in indoor air were detected in the immediate vicinity of active (wet) microbial amplification sites.

When furnishings and heating, ventilating, and air-conditioning (HVAC) system components are disturbed (aggressive sampling), concentrations of airborne fungi in the immediate vicinity generally become elevated relative to outdoor concentrations. However, concentrations vary widely and a uniform interpretation of results cannot be obtained by simple comparison of the indoor to outdoor concentration ratio.

The average concentration of TVOC indoors was about three times that present outdoors. However, wide variations in indoor/outdoor concentration ratios of TVOC occur in commercial office buildings as a function of contaminant source strengths and because of HVAC system operational variables. The ratio of indoor/outdoor TVOC varied from 4 to 16 under conditions of minimum outdoor air ventilation to less than 2 when large amounts of outdoor air were being used.

The minimal concentration of NO_2 found in the outdoor air around two of seven buildings studied in the New York City area exceeded 0.05 parts per million (ppm). In one building where the HVAC system outdoor air inlet was sporadically contaminated by vehicular combustion products, indoor levels of NO_2 reached peak concentrations of 0.6 to 0.7 ppm.

Because of numerous indoor and outdoor variables that affect concentrations of mesophilic fungi, TVOC, and NO_2, typical concentrations of these air contaminants cannot be specified. Interpretation of air sampling data is best made on a building-by-building basis after all variables affecting building and HVAC system performance are considered.

INTRODUCTION

Air sampling in 25 office buildings where occupants reported the widespread occurrence of annoyance and discomfort complaints on at least one floor or zone was carried out for one or more of the following contaminants: mesophilic fungi, TVOC, and NO_2. As a reference for deciding what is "typical," air sampling was also carried out in protected outdoor locations, generally on the roof, away from potential sources of these air contaminants. Our objective was to determine if the indoor concentrations of airborne fungi, TVOC, and NO_2 differed in some predictable way from those present in the outdoor air.

Microbiological Sampling

The sampling methods used to collect airborne fungi are described elsewhere (ACGIH 1987; Morey et al. 1986a, b). Viable fungi were collected onto malt extract agar using a sieve impactor (no sizing; respirable and nonrespirable particulate collected on same plate) operating at a flow rate of 6.4 cubic feet per minute (cfm) (180 liters per minute [L/min]). Incubation temperatures for fungi were 25°C.

Volatile Organic Compound Sampling

Most samples for TVOC were collected by using battery-powered portable pumps to draw air at measured flow rates through glass tubes containing 2,6-diphenyl-p-phenzlene oxide. In the laboratory, the sample is thermally desorbed directly into a gas chromatography/mass spectral analyzer. The spectra from the desorbed sample is evaluated via a computer data base interface with the unit to identify the individual components in the sample. The quantity of each compound present is determined. Analytical results, which include any necessary corrections for parallel blank and recovery determinations, were used in conjunction with sampling data (volume of air sampled) to calculate the concentrations of airborne TVOC represented by each sample, expressed in micrograms analyte per cubic meter of air (ug/m^3).

A few samples for TVOC were collected by using organic vapor monitor badges. The contaminant enters the monitor by diffusion and is adsorbed by an active adsorbent medium (charcoal) inside the badge. The amount of contaminant adsorbed is determined by exposure time and contaminant concentration present in the sampled environment. A measured volume of carbon disulfide is added to the monitor to desorb the collected organic vapors. A portion of the desorbing solvent containing the organic contaminants is withdrawn from the monitor and analyzed by gas chromatography. Quantities of each analyte present are determined by comparison of areas under the sample chromatogram peaks with areas under chromatogram peaks for standards (as mineral spirits) prepared in carbon disulfide.

Nitrogen Dioxide Sampling

Integrated long-term area samples were collected by drawing air at measured flow rates (50 to 200 milliliters per

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TABLE 1

Airborne Fungi in Seven Buildings Where Quiescent and Aggressive Sampling Was Carried Out

Building, Time of Year	Fungi in Outdoor Air (cfu/m³)	Ratio Indoor/Outdoor Fungal Concentrations			Environmental Conditions in Building
		Quiescent Sampling in Offices	Quiescent Sampling in HVAC System	Aggressive Sampling in Office or HVAC System	
A, January	36	0.21	—	5.5	Excessive moisture RH = 60 to 80% dewpoint 62 to 72 °F
B, October	200	0.08	0.08	10 to 100	Dry, moldy insulation on inside of air handling units
C, June	200	0.1 to 1.0	—	—	Floors 1 to 4; RH = 30-40%; dewpoint 43 to 48 °F
C, June	200	2.5 to 5	—	—	Basement; RH = 60 to 70%; dew point 62 °F to 70 °F
D, November	630	0.07	—	13.2	Ceiling tiles dry but damaged by previous floods; induction units poorly maintained
E, December	100	0.15	—	0.5	Induction units poorly maintained
E, September	75	0.13	—	0.5	Induction units poorly maintained
F, August	200	0.25	0.5	1.5	Excessive moisture on day before sampling; RH = 50% on date of sampling
G, May	85	0.16	—	2.0	Fan coil units poorly maintained

cfu/m³ means colony forming units per cubic meter of air.

minute) for at least four hours through a sampling tube containing a 400-milligram triethanolamine-impregnated molecular sieve. Laboratory analysis is accomplished by transferring each triethanolamine-impregnated molecular sieve section to a flask where the nitrogen dioxide is desorbed and hydrolyzed in an aqueous triethanolamine solution to yield nitrite ion. An aliquot is treated with hydrogen peroxide, sulfanilamide, and n-(1-naphthyl)-ethylenediamine dihydrochloride. The reacted nitrite ion is measured with a spectrophotometer in a 1-centimeter cell at 540 nanometers.

RESULTS AND DISCUSSION

Microorganisms

Results of air sampling for mesophilic fungi in seven buildings are presented in Table 1. Air sampling was carried out in offices during normal working hours, under normal environmental conditions, with HVAC systems operating in a manner typical for each building. This is referred to as quiescent sampling. Sampling was also carried out as a reference in the outdoor air and, in a few buildings, within HVAC system air-handling units themselves (also quiescent sampling; Table 1). In a majority of buildings, airborne fungi were also collected in the occupied space or in the HVAC system when furnishings and mechanical components (for example, induction units) were manipulated by gentle pounding or agitation. This mode of sampling is referred to as "aggressive."

Concentrations of fungi collected indoors are expressed in terms of the ratio of the average indoor level divided by that present outdoors. With the exception of the basement of Building C, the ratio of the indoor/outdoor concentration of mesophilic fungi was substantially less than unity. Thus, in most buildings the concentration of fungi collected indoors is only 10% to 25% of that found at the same time in the outdoor air.

When furnishings in the occupied spaces or components of the HVAC system such as induction units, internal insulation, or drain pans are mechanically disturbed (aggressive sampling) levels of airborne fungi in the immediate vicinity generally become elevated above unity (Table 1). However, concentrations vary widely and a uniform interpretation of results cannot be obtained by simple comparison of ratios in Table 1. For example, despite the elevated concentrations of fungi (mostly *Cladosporium*) released during aggressive sampling in Building B, few of these organisms reach the occupied space in this otherwise "healthy" building. On the other hand, in Building F, several occupants were affected by an illness in which fever and chills were characteristic symptoms and yet the indoor fungal concentrations during aggressive sampling were just slightly elevated relative to those outdoors.

Interpretation of air sampling data for fungi can best be achieved on a building-by-building basis where factors such as environmental conditions in occupied spaces, HVAC system variables, and types of microorganisms are considered. A brief consideration of sampling results for each building listed in Table 1 follows.

Building A. Occupants in a zone of this building had complained for several months about uncomfortable thermal environmental conditions. A malfunctioning humidifier in the air-handling unit serving this zone resulted in elevated moisture levels in indoor air (relative humidity 60% to 80%; dew point 62° to 72°F).

Air sampling in offices under aggressive conditions showed that fungi were present at levels about five times higher than outdoor concentrations. Indoor fungi were dominated by *Aspergillus*, *Penicillium*, *Cladosporium*, and *Aureobasidium*, whereas *Cladosporium* alone was the dominant outdoor genus. Sampling in Building A thus indicated that microbiological amplification was occurring indoors, a con-

TABLE 2

Concentrations of Total Volatile Organic Compounds in 15 Buildings

Location	Concentration of TVOC in ug/m³	Number Samples	Percent of Total Samples
Indoors	≧ 2000	6	6
Indoors	≧ 1000 to 1999	15	14
Indoors	≧ 500 to 999	25	23
Indoors	≧ 200 to 499	31	28
Indoors	≧ 100 to 199	19	17
Indoors	≧ 1 to 99	13	12
Outdoors	≧ 500 to 999	3	13
Outdoors	≧ 200 to 499	5	22
Outdoors	≧ 100 to 199	7	30
Outdoors	≧ 1 to 99	8	35

Average of 109 indoor samples = 660 ug/m³
Average of 23 outdoor samples = 232 ug/m³

clusion that could also have been surmised from the high moisture levels characteristic of the affected zone.

Building B. During routine HVAC system preventive maintenance, it was observed that the interior insulation in air-handling units at locations downstream of the cooling coil section was covered with a mildew-like layer. The dominant fungus in the contaminated insulation was *Cladosporium*. Quiescent sampling both in offices and in active air-handling units (3 in from insulation) indicated that concentrations of fungi were less than 10% of outdoor levels (Table 1). However, when similar sampling in air-handling units was carried out simultaneously with slight agitation of insulation, recoveries of airborne fungi increased by two or three orders of magnitude.

Clearly the internal insulation in air-handling units was an amplification site for the common environmental fungus *Cladosporium*. Since the insulation was dry at the time of sampling, low concentrations of fungi in offices under quiescent conditions were probably due to the absence of active fungal growth and sporulation.

Building C. Occupants in a four-story building became concerned about a strong musty smell that was noticeable especially on lower floors. The basement had recently been flooded and its walls were wet and covered with a fungal growth.

Quiescent sampling in the basement showed that concentrations of airborne fungi were higher than outdoor levels. Sampling on floors one through four, however, failed to demonstrate elevated fungal concentrations. In this building, quiescent air sampling for fungi was effective in demonstrating the presence of an amplification site only in its immediate vicinity. The conclusion that wet basement walls were amplification sites for microorganisms was obvious (visually) prior to the initiation of sampling.

Building D. Quiescent and aggressive air sampling were carried out in an office where floods earlier in the year had damaged several ceiling tiles. Levels of fungi in offices during quiescent sampling (mostly *Cladosporium* and *Penicillium*) were less than 10% of outdoor levels (mostly *Cladosporium*, *Epicoccum*, and *Aureobasidium*). When damaged but dry ceiling tiles and dry insulation inside induction units were disturbed, concentrations of fungi (mostly *Cladosporium*, *Penicillium*, and *Epicoccum*) in offices increased to more than

TABLE 3

Concentrations of Total Volatile Organic Compounds in Building E Under Different HVAC System Outdoor Air Ventilation Operational Modes

Time of Year and Outdoor Air Ventilation	Average Concentration of Total Volatile Organic Compounds*		Indoor/Outdoor Ratio
	Indoors	Outdoors	
June; Minimum Outdoor Air	1420	—	—
November; Minimum Outdoor Air	1270	310	4.1
December; Minimum Outdoor Air	445	93	4.8
September; Minimum Outdoor Air	268	16	16.0
September; Maximum Outdoor Air	71	48	1.48
October; Maximum	85	50	1.70

*Concentration in micrograms per cubic meter of air

10,000 colony-forming units per cubic meter of air (cfu/m³) or about 10 times the outdoor level. It was apparent from this study that aggressive, not quiescent, sampling was effective in demonstrating the presence of dry microbial reservoirs. Of course, it could be surmised without sampling that water-damaged ceiling tiles were likely microbial amplification sites.

Building E. Quiescent air sampling was carried out for three days in a high-rise building in December and then during the following September. Concentrations of fungi recovered indoors averaged 13% to 15% of outdoor levels.

Aggressive air sampling near induction units that were poorly maintained showed that recoveries averaged only about half of those present in outdoor air. Thus, air sampling in this building was unsuccessful in demonstrating any significant fungal amplification site. Subsequent studies in this building have shown that HVAC system components are amplification sites for bacteria, including *Flavobacterium* and streptomycetes.

Building F. Quiescent and aggressive air sampling were carried out in a small building four to five days after an episode of illness characterized by fever, chills, and breathing difficulties. During the outbreak, relative humidity indoors exceeded 60% and dew point temperatures were above 62°F. When sampling was carried out, moisture levels in the occupied spaces had declined considerably.

Even during aggressive sampling, levels of fungi indoors only slightly exceeded those present in the outdoor air. Air sampling, however, did reveal that *Chaetomium* was a predominant fungus indoors but not outdoors.

Building G. Quiescent air sampling in an office with reported sick building syndrome complaints consistently showed that indoor recoveries were only about 16% of those found in outdoor air. *Cladosporium* dominated indoor and outdoor fungi. When poorly maintained fan coil units were disturbed, levels of fungi indoors increased to about two times those outdoors. *Aspergillus* dominated the fungal recoveries indoors during aggressive sampling.

VOLATILE ORGANIC COMPOUNDS

Air sampling for TVOC was carried out in 15 office buildings using 2,6-diphenyl-p-phenzlene oxide sorbent and gas

TABLE 4

Nitrogen Dioxide Concentrations in Seven Buildings in the New York City Area

Building	Nitrogen Dioxide Concentrations*		
	Protected Outdoor Air	Indoor Air	HVAC System Outdoor Air Inlet
Bldg. E	< 0.07	< 0.06 to 0.10	—
Bldg. E	—	0.2 to 0.3	—
Bldg. F	0.04	0.20	0.08
Bldg. G	0.05	0.09 to 0.10	—
Bldg. H	0.10	< 0.07 to 0.09	—
Bldg. I	0.10 to 0.11	0.03 to 0.16	—
Bldg. J	< 0.02	< 0.02 to 0.20	—
Bldg. K	< 0.02 to 0.05	< 0.03 to 0.60	< 0.04 to 0.60
Bldg. K	0.03 to 0.08	< 0.04 to 0.70	0.03 to 2.0

< means less than
*Concentrations in parts per million

chromatography-mass spectrometry analysis (Table 2). The average concentration of TVOC indoors was 660 ug/m³ while that outdoors was 232 ug/m³ (indoor/outdoor ratio = 2.84).

Approximately 20% of the 2,6-diphenyl-p-phenzlene oxide TVOC samples collected in offices equaled or exceeded a concentration of 1000 ug/m³. Six percent of the samples exceeded or equaled 2000 ug/m³. Concentrations of TVOC in outdoor air never exceeded 1000 ug/m³. Thirty-five percent of the outdoor air samples had TVOC concentrations less than or equal to 100 ug/m³. Only 12% of indoor samples were characterized by TVOC concentrations less than or equal to 100 ug/m³.

The authors had the opportunity to measure TVOC in one New York City high-rise office building (Building E) on four occasions when the HVAC system was using minimum outdoor air and on two additional occasions when maximum outdoor air ventilation (economizer cycle) was being used. The concentration of TVOC indoors was significantly elevated above outdoor levels under minimum outdoor air ventilation conditions (Table 3). The indoor/outdoor ratio of TVOCs in Building E under minimal outdoor air ventilation conditions ranged from 4 to 16. By contrast, under maximum outdoor air ventilation conditions, the indoor/outdoor ratio was just slightly greater than unity (1.4 to 1.7).

In one building (Building H) during a three-week period, TVOCs were measured by passive charcoal monitor. The offices of one tenant were contaminated by odors from the printing press operations of another tenant. Offices of the former tenant were characterized by occupant complaints of eye, nose, and throat irritation. Average concentrations of TVOC (as mineral spirits) indoors (time-weighted average for three weeks) was 22,500 ug/m³. Concentrations outdoors but within 6 ft of the building envelope averaged 1450 ug/m³. At a site remote from the building the TVOC concentration was less than 200 ug/m³ (the limit of detection of the sampling technique used).

NITROGEN DIOXIDE

Air sampling for NO_2 and other products of combustion were carried out in seven buildings in the New York City area (Table 4). Landlords or tenants in these buildings were concerned about the possible entry of combustion gases into offices from parking garages, loading docks, or poorly located HVAC system outdoor air inlets. Sampling for NO_2 in all buildings was carried out in the outdoor air, generally on the roof, as far away as possible from vehicular traffic or exhaust stacks that may contain combustion gases. In one building (Building K), extensive sampling was also carried out in the outdoor air inlet of the air-handling unit providing conditioned air to occupied spaces.

In two of the seven buildings, the lowest concentration of NO_2 in outdoor air (Buildings H and I) was greater than 0.05 ppm. Indoor concentrations of NO_2 generally exceeded outdoor levels, a result ascribed to contamination of the HVAC system outdoor air intake with combustion gases.

In one building (Building K) where sampling was carried out round-the-clock for six days, the authors had the opportunity to compare NO_2 concentrations in the indoor air with those outdoors on the roof and in the outdoor air inlet of the HVAC system. The outdoor air inlet for the HVAC system was located at grade level near a loading dock. Approximately 40% of the occupants in one office reported periodic complaints of headache, disorientation, nausea, burning eyes, and nosebleeds. Complaints of gasoline or diesel odors were also reported at the same time. Because of sporadic disruption of productivity, management had these offices vacated pending a resolution of the problem.

Concentrations of NO_2 in outdoor air in a protected location on the roof of Building K never exceeded 0.08 ppm (Table 4). In the affected office, NO_2 concentrations also did not exceed 0.08 ppm except on two occasions when levels rose as high as 0.6 to 0.7 ppm. On one of these occasions the concentration of NO_2 in the outdoor air inlet of the air-handling unit approached 2.0 ppm. On the other occasion it was assumed that a high concentration of NO_2 in the HVAC system outdoor air inlet preceded sampling in the occupied spaces. This building-associated problem was caused by poor HVAC system design, namely locating the outdoor air intake at grade level near a loading dock that would be periodically contaminated by combustion gases.

CONCLUSIONS

Microbiological Sampling

With the exception of only one building (Building C, Table 1), concentrations of fungi collected during quiescent sampling in the office environment were 10% to 25% of those in the outdoor air. Mechanisms such as HVAC system filtration and sedimentation of large spores are likely preventing the entry of most fungi into the indoor air. Elevated levels of fungi in indoor air during quiescent sampling are likely to be detected only in the immediate vicinity of active (wet) microbial amplifiers.

In some buildings with obvious but inactive amplifiers (Table 1, Building B), indoor fungal levels during quiescent sampling were much less than those in the outdoor air. A thorough visual examination of the building, including its HVAC system, is required to detect microbial reservoirs and amplification sites. Aggressive sampling in the immediate vicinity of the reservoir or amplifier may, however, be useful to confirm the visual impression that a microbial amplification site exists.

Aggressive sampling showed that elevated fungal levels (5 to 100 times that present in outdoor air) existed in three buildings (Buildings A, B, and D, Table 1). There was no indication, however, that complaints suggestive of hypersensitivity lung illness were characteristic of these buildings. In one building (Table 1, Building F) where occupants offered

complaints suggestive of hypersensitivity lung illness, aggressive sampling revealed only slightly elevated levels of fungi indoors. These data suggest that interpretation of air sampling data for microorganisms should be made with caution. Recoveries of viable particulate are affected by numerous variables including the condition of the amplifier (for example, wet or dry) and the time interval between the onset of the water problem and the onset of sampling. The possibility that occupant problems are related to agents other than viable fungi should not be overlooked (Morey 1988).

Air sampling for fungi should ideally be carried out only after a preassessment phase in which visual inspection of the building is carried out to identify microbial reservoirs and amplification sites (ACGIH 1987). It is generally much easier to carry out remedial actions than to prove that a microbial agent is causing occupant building-related illness.

Many variables affected microbial concentrations in indoor air. The perception of what is "typical" depends on the availability of water and nutrients, the number and kinds of fungi present outdoors and indoors, the operational status of the HVAC system, and the types of activities occurring in the occupied spaces. All these variables most be considered in deciding if indoor microbiological parameters are typical or normal. It should always be kept in mind that air sampling for microorganisms in itself cannot be used to predict potential adverse health responses in the office environment (ACGIH 1987; Morey 1988).

Volatile Organic Compound Sampling

The average concentration of TVOC (2,6-diphenyl-p-phenzlene oxide data only) indoors was elevated above outdoor levels in most of the offices studied. Wallace (1987) has shown that indoor/outdoor ratios for TVOC in residential environments significantly exceed unity.

In Building E we measured TVOC levels under both minimal and maximum outdoor air ventilation conditions. Under minimal outdoor air ventilation, the ratio of indoor to outdoor air TVOC concentrations was significantly above unity. Under economizer conditions, however, indoor levels were just slightly elevated above outdoor levels. These data from Building E suggest that wide variations in TVOC concentrations can be expected dependent upon the amount of outdoor air being utilized in conditioned air. Therefore, predictions on what is typical in terms of indoor TVOC concentrations and indoor/outdoor ratios are highly dependent on office building HVAC operational variables.

Molhave (1985) has speculated that a threshold for sensory perception to TVOC in indoor environments occurs at levels equal to or exceeding 1000 ug/m^3. Among the 109 air samples collected in office environments, 20% were characterized by TVOC concentrations equal to or exceeding 1000 ug/m^3, and 6% had concentrations equal to or exceeding 2000 ug/m^3.

Nitrogen Dioxide Sampling

Reference to outdoor air in protected locations generally provides guidance as to what is typical for a given geographical area in terms of concentrations of indoor combustion gases. In two of the seven buildings in Table 4, the minimal concentration of NO_2 outdoors was consistently greater than 0.05 ppm, which is, therefore, above the acceptable level of NO_2 recommended by ASHRAE Standard 62-1981R (ASHRAE 1981). In these buildings, the NO_2 levels indoors were similar to or just slightly elevated relative to outdoor concentrations

In several buildings, however, the maximum concentration of NO_2 indoors (Buildings F, J, and K) greatly exceeded the outdoor level. We were fortunate in Building K to simultaneously correlate high indoor levels of NO_2 with even higher levels of this gas in the HVAC system outdoor air inlet. The collective data of this study can be interpreted as suggesting that when indoor levels of NO_2 greatly exceed (perhaps two to four times) the concentrations in protected outdoor areas, the air indoors is no longer "typical." Certainly when indoor levels of NO_2 exceed 0.5 ppm, even on a sporadic basis, widespread occupant problems can be expected.

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DISCUSSION

Jeffrey C. Olcott, Envirogenics Inc., Pennington, NJ: Of the studies you have described, how many were corroborated by clinical findings giving a diagnosis of hypersensitivity pneumonitis?

P.R. Morey, Clayton Environmental Consultants, Wayne, PA: None. However, in several of the studies involving buildings with fungal problems, private physicians had expressed the opinion that one or more occupants had symptoms suggestive of hypersensitivity lung illness.

Carl N. Lawson, LRW Engineers, Tampa, FL: On the building you checked, did any duct liners have a vinyl coating and, if so, was there any fungus growth?

Morey: None of the air-handling units had, to my knowledge, a vinyl liner covering internal insulation. However, in several instances, internal liners were sealed, apparently with an epoxy compound. Fungal and bacterial colonization of internal insulation in air-handling units downstream of cooling coils and in major air supply ducts was always most intense where the insulation exposed to the airstream was very porous. In one instance, the porous insulation (already heavily contaminated with *Penicillium*) was sealed with a polyvinyl acetate compound. Within two to three months, this sealant (polyvinyl acetate) became a substrate that supported a luxuriant fungal growth.

A COMPARISON OF RADON PROGENY WORKING LEVELS IN NEWER AND OLDER HOUSES IN WINNIPEG, CANADA

Gary Proskiw, P.Eng. **Peter Piersol, P.Eng.** **Mark Riley**

ABSTRACT

Radon progeny working levels were monitored over a one-year period in 20 new houses located in Winnipeg, Manitoba, Canada. Sixteen were constructed to the R-2000 standard for energy-efficient housing, while the remaining four were relatively conventional structures. All contained some form of mechanical ventilation system. Radon progeny working levels were found to be lower in the 20 project houses relative to those reported in a study of older, conventional houses in the same city. The geometric mean values for the R-2000, new conventional, and older conventional houses were 0.006 WL, 0.009 WL, and 0.017 WL, respectively, with the percentage of measurements exceeding the EPA guideline of 0.020 WL being 4%, 13%, and 40%, respectively. Leakier below-grade construction in the older houses was suggested as a possible explanation for the observed differences. The wide variation in observed levels for houses in the same city indicates that geographic location may not, by itself, be a reliable parameter for predicting indoor concentrations. Little correlation was observed in the 20 project houses between radon progeny working levels and independently measured total air change rates (mechanical and natural). From the perspective of establishing indoor air quality standards, air change rate was not found to be an effective mechanism for achieving radon control objectives for levels on the order of 0.020 WL.

INTRODUCTION

Radon is known to be present in all parts of Canada, although in varying concentrations. Originating in the underlying geological formations and soils, the gas can enter a house through diffusion and by airborne transport via physical discontinuities between the soil and the structure. Commonly used radon control measures include ventilation to dilute interior concentrations and source control to reduce soil gas/radon entry. The latter typically employs measures to maximize the airtightness of the below-grade and/or surface components of the structure to minimize potential infiltration sites. Other measures successfully demonstrated include sub-slab ventilation and pressurization of the basement to reduce infiltration.

Assessing the health impact of prolonged exposures to radon is difficult because the effects may not become evident for several years and may be obscured by other causes. However, it is generally accepted that exposure to radiation is harmful and, for the general public, the major exposure to radiation is reported to be inhalation of radon progeny (George 1985).

The problem of assessing the health risk has made the establishment of exposure standards difficult. At present, there are no Canadian guidelines for radon exposure in residences, although a value of 0.100 working levels (WL) has been suggested as an action level. The current U.S. Environmental Protection Agency guideline is 0.020 WL (EPA 1988). Swedish limits vary depending on the type of structure: 0.108 WL for existing dwellings, 0.054 WL for renovated buildings, and 0.019 WL for new dwellings (Swedemark and Mjones 1984).

RESEARCH PROGRAM

Project Houses

Radon progeny working levels and total air change rates were monitored in 20 detached, occupied bungalows between March 1986 and February 1987. The houses were part of the Flair Homes Energy Demo/Canadian Home Builders Association Flair Mark XIV project, located in Winnipeg, MB, Canada. All had been constructed in 1985 and 1986 by a single builder. Nineteen were located side-by-side, while the twentieth was situated approximately 1 km away.

The houses were very similar in size and layout: two floor plans were used with main floor areas of 60 m^2 and 85 m^2, respectively. Sixteen were designed to the R-2000 standard, with the remaining four constructed using relatively conventional practices. The R-2000 standard for residential construction includes requirements for building energy usage, airtightness, heating equipment, and mechanical ventilation systems.

All of the houses had cast-in-place concrete basements and floor slabs. Sixteen used interior insulation with polyethylene air/vapor barriers on the walls, stapled in place with some sealing to reduce air leakage. Four of the houses used exterior basement insulation systems with exposed concrete on the interior. Basement floor slabs were cast onto aggregate placed on undisturbed soil. Four of the slabs used 38 mm (1 1/2 in) semi-rigid glass fiber insulation between the aggregate and the concrete. These also employed passive sub-slab vents intended to generate a pressure differential across the floor slab by using wind action to induce an airflow through a roof ridge vent that was connected to the underside of the slab. All of the houses used standard basement floor drains without open sumps; however, four employed floor drain cover traps to control air infiltration. Weeping tiles were connected to the floor drains above the standard sewer trap. Domestic water was provided by mains supply.

The houses used mechanical ventilation systems ranging from intermittent, small-capacity bathroom exhaust fans to heat recovery ventilators (HRV) designed to run continuously and provide fresh air distribution to all zones of the house. Sixteen of the mechanical systems utilized multi-speed controls which permitted flow rates to be automatically or man-

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TABLE 1

Description of Project Houses

Houses	Year of Completion	Location of Basement Wall Insulation	Basement Slab Insulation	Floor Drain Cover, Passive Sub-Slab Vent	Space Heating System	Ventilation System	Envelope Operating Pressure Regime	Energy Performance Standard
1, 2	1985	Interior	No	No	Forced Air Electric Furnance	Heat Recovery Ventilator Connected to Ductwork	Balanced	R-2000
3, 4	1985	Interior	No	No	Forced Air Electric Furnance	Heat Recovery Ventilator Connected to Ductwork	Slightly Positive	R-2000
5, 6	1985	Interior	No	No	Forced Air Electric Furnance	Heat Recovery Ventilator Connected to Ductwork	Slightly Negative	R-2000
7, 8	1985	Interior	No	No	Forced Air Electric Furnance	Central Exhaust	Slightly Negative	Conventional
9, 10	1985	Interior	No	No	Forced Air Gas Furnance	Bathroom Exhaust Fan	Slightly Negative	Conventional
11, 12	1986	Exterior	Yes	Yes	Electric Baseboards & Small Capacity Heat Pump	Exhaust-Only Heat Pump Heat Recovery Ventilator	Slightly Negative	R-2000
13, 14	1986	Interior	No	Yes	Forced Air Electric Furnance	Heat Recovery Ventilator Connected to Ductwork	Slightly Negative	R-2000
15, 16	1986	Interior	No	No	Integrated Forced Air Pump Heating/ Ventilation System	Air-to-Air Electric Heat	Balanced	R-2000
17, 18	1986	Interior	No	No	Electric Baseboards	Heat Recovery Ventilator with Dedicated Supply Ductwork	Balanced	R-2000
19, 20	1986	Interior	No	No	Electric Baseboards	Heat Recovery Ventilator with Dedicated Supply Ductwork	Balanced	R-2000

TABLE 2

Radon Progeny Levels, New Winnipeg Houses

	Number of Houses	Geometric Mean (WL)	Median (WL)	Measurements >0.020 WL Number	%	Measurements >0.100 WL Number	%
R-2000 Houses							
March 1986	6	0.004	0.006	0	0%	0	0%
August 1986	14	0.007	0.006	1	7%	0	0%
October 1986	16	0.009	0.009	1	6%	0	0%
February 1987	14	0.004	0.003	0	0%	0	0%
Cumulative	50	0.006	0.007	2	4%	0	0%
Conventional Houses							
March 1986	4	0.009	0.009	0	0%	0	0%
August 1986	4	0.011	0.012	0	0%	0	0%
October 1986	4	0.010	0.015	2	50%	0	0%
February 1987	4	0.007	0.008	0	0%	0	0%
Cumulative	16	0.009	0.009	2	13%	0	0%

TABLE 3

Total Air Change Rates

	Number of Houses	Mean (ach)	Standard Deviation (ach)	Median (ach)
R-2000 Houses				
March 1986	6	0.28	0.18	0.26
October 1986	16	0.30	0.16	0.29
February 1987	15	0.43	0.13	0.45
Cumulative	37	0.35	0.16	0.36
Conventional Houses				
March 1986	4	0.16	0.05	0.14
October 1986	4	0.15	0.05	0.17
February 1987	4	0.20	0.07	0.18
Cumulative	12	0.17	0.05	0.17

ually adjusted. Ventilation rates for the R-2000 houses were established to conform to the R-2000 Home Program Design and Installation Guidelines for Ventilation Systems (1986), which require a minimum continuous mechanical ventilation rate of 0.35 ach (or possibly greater, depending on the number of rooms). Actual air change rates achieved during the monitoring program were often noticeably different due to equipment malfunction or homeowner intervention with the operation of the ventilation system.

All of the houses, including the conventional structures, were constructed with relatively tight building envelopes to minimize natural infiltration. Airtightness levels, determined in accordance with CGSB Standard 149.10-M (1986), ranged from 0.44 to 2.20 ach at 50 Pascals when measured in February 1987. A detailed description of the houses is given in Table 1.

MONITORING PROGRAM

Radon progeny working levels were measured in March 1986, August 1986, October 1986, and February 1987 with an active time-integrating, track-registering sampler that used an air pump to draw controlled amounts of air across a detecting surface. The samplers were installed in a representative location in the house basements and operated continuously for periods of approximately one week. Analysis of the exposed detector substrate was then performed.

Total air change rates were measured simultaneously during three of the four sampling periods using the capillary adsorption tube sampling (CATS) technique (Dietz and Cote 1982). This method has been found to display good agreement with the constant concentration sulphur hexafluoride technique when relatively constant total air change rates are encountered (Piersol and Mayhew 1987). Four calibrated sources, which emitted an inert perfluorocarbon tracer gas, were situated around the house on exterior walls. Two or four samplers that adsorbed the tracer were installed at central locations on each level. The amount of tracer adsorbed by the samplers was determined using gas chromatographic analysis and related to the total air change rate experienced by the house during the monitoring period.

RESULTS

Observed radon progeny working levels and total air change rate data are given in Tables 2 and 3.

DISCUSSION

Measured radon progeny working levels were generally low relative to the EPA guideline of 0.020 WL, with 4% and 13% of the measurements exceeding this level in the R-2000 and conventional houses, respectively. Seasonal variations were noted, with the highest levels recorded in the summer and fall. Geometric mean and median levels were lower in the R-2000 houses compared to the conventional structures during all four monitoring periods. A similar study of radon gas levels was performed in the same city by Yuill (1988) during the summer and fall of 1987 in which radon gas levels were measured in 70 Winnipeg houses using one-week sampling periods. These houses had been constructed between 1902 and 1980 and were representative of older, existing housing stock in the city. A summary of these results is shown in Table 4, with the radon gas levels converted to working levels using an equilibrium ratio of 0.5. One of the most striking results is that levels in the older houses were much higher than those in the 20 houses in the Flair project. The geometric mean for the older houses was 0.017 WL vs. 0.006 WL and 0.009 WL, respectively, for the R-2000 and conventional, new houses in the Flair project. Twenty-eight of the 70 older houses, or 40%, had measured levels exceeding 0.020 WL, compared with 4% and 13%, respectively, of the measurements taken in the R-2000 and conventional houses.

Although reasons for the behavioral differences between the newer and older houses need further investigation, one possible explanation is the reduced level of below-grade airtightness in the older structures. Winnipeg is located in an area of moisture-susceptible soils which can expand and contract with variations in moisture content. Foundation distress caused by differential movement of the basement is common. Older structures are particularly vulnerable because their foundations were often constructed without the structural integrity of modern foundations. The mean airtightness of the 70 older houses was reported as 6.78 ach_{50}, whereas the R-2000 and newer, conventional structures in the Flair project averaged 1.07 ach_{50} and 1.62 ach_{50}, respectively. (A difference was noted in the airtightness testing procedure between the two studies in that the 70 older houses were tested with all intentional openings unsealed. This would have resulted in elevated ach_{50} values.)

The wide variation in radon progeny levels found in these two studies for houses in the same city indicates that geographic location was not observed to be a dominant factor in determining indoor concentrations. This should be consid-

TABLE 4

Radon Progeny Levels Reported by Yuill, Older Conventional Winnipeg Houses

	Number of Houses	Geometric Mean (WL)	Median (WL)	Measurements >0.020 WL Number	%	Measurements >0.100 WL Number	%
Summer & Fall 1987	70	0.017	0.017	28	40%	0	0%

ered in attempts to map radon "hot zones" since spurious results could be produced by factors such as differences in the airtightness of below-grade components of the envelope.

The relationship between radon progeny working levels and total air change rate is classically expressed using Equation 1, which was developed on the basis of a simple mass balance on a one-compartment model and assumes perfect mixing of the indoor air:

$$Ci = Co + N/V_t \quad (1)$$

where

Ci = indoor concentration
Co = outdoor concentration
N = net pollutant source generation rate
V_t = total air change rate

The source term, N, is assumed to be independent of the indoor concentration and air change rate. Equation 1 applies to a single structure with a constant outdoor pollutant concentration and source strength. If used to describe the behavior of a population of houses, which may or may not have similar characteristics, Equation 1 can be rewritten as:

$$Ci = Co' + N'/Vt \quad (2)$$

The terms Co' and N' describe representative effective values of the outdoor concentration and source strength for the entire population.

Radon progeny working levels are plotted against total air change rates in Figure 1 using all measurements made during the monitoring period. This produced a correlation coefficient of 0.30. The implications of this are important. For a single house, the inverse relationship described by Equation 1 has been observed (Rector 1985), although variations in source strength can produce measurable departures from the anticipated behavior. However, Equation 2 was not found to successfully describe the behavior of a population of houses, even though they were located very close together and were of similar age. The implication is that the air change rate and hence the mechanical ventilation rate would not have been successful mechanisms to achieve radon control objectives at the range of levels encountered (typically around 0.020 WL). Other measures such as source control should be seen as the first line of defense.

The impact upon radon progeny levels of house pressurization, passive sub-slab ventilation, and floor drain cover traps will be discussed in a future paper.

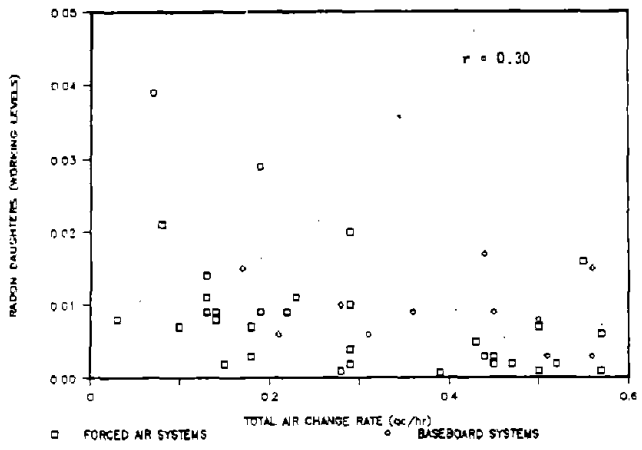

Figure 1 *Radon progeny vs. total air change rate (March 1986, October 1986, January 1987)*

CONCLUSIONS

Radon progeny working levels were monitored over a one-year period in 20 new, low-leakage, occupied houses equipped with mechanical ventilation systems located in Winnipeg, Canada. Levels were lower in the R-2000 energy-efficient structures than those in the conventional structures of the same age. However, levels in both the R-2000 and conventional houses were lower than those reported in a study conducted in the same city using a random sample of house types and ages. This latter group was composed largely of older, conventional structures with leakier building envelopes. Geometric mean radon progeny working levels for the R-2000, new conventional, and older conventional houses were 0.006 WL, 0.009 WL, and 0.017 WL, respectively. The percentages of measurements which exceeded the EPA guideline of 0.020 WL for the three groups were 4%, 13%, and 40%, respectively.

The wide variation in observed radon progeny levels for houses located in the same city suggests that geographic location may not, by itself, be a reliable parameter for predicting indoor concentrations.

Radon progeny working levels were compared to independently measured total air change rates and it was found that air change rate was a poor predictor of radon progeny working levels. From the perspective of establishing indoor air quality standards, total air change rate and hence mechanical ventilation rate were not observed to have been effective mechanisms for achieving radon control objectives for levels on the order of 0.020 WL.

ACKNOWLEDGMENTS

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DISCUSSION

Jeffrey C. Olcott, Envirogenics Inc., Pennington, NJ: Based on your data and the current 0.02 wl "guideline," can you comment on the feasibility of meeting the proposed U.S. EPA guideline of 0.2 to 0.7 pCi/L?

G. Proskiw, UNIES Ltd., Winnipeg, Manitoba, Canada: I believe it will be very difficult to reach on a production basis, particularly without an effective sub-slab depressurization system. The primary radon control measures used in our houses were improved below grade airtightness and mechanical ventilation, both of which were carefully constructed/installed. However, 94% and 77% of the measurements exceeded 0.2 and 0.7 pCi/L, respectively.

William A. Turner, Harriman Associates, Auburn, ME: Has any effort been made to characterize heating types—hot air vs. hot water—in the conventional homes? As one might expect, hot air systems have one-half the level of radon progeny as hot water systems due to plate-out from air movement.

Proskiw: Not yet. It will be performed once we have three years' worth of monitoring results (one year's worth of data were reported in the paper).

Carl N. Lawson, LRW Engineers, Tampa, FL: Is there any ground treatment, such as Visqueen, to keep the radon dormant?

Proskiw: No.

THE INFLUENCES OF HVAC DESIGN AND OPERATION ON RADON MITIGATION OF EXISTING SCHOOL BUILDINGS

K.W. Leovic A.B. Craig D. Saum

ABSTRACT

A number of public school buildings in Maryland and Virginia have been qualitatively surveyed to assess the various school characteristics that may influence radon entry and potentially impact radon mitigation system design and performance. Results indicate that one of the most significant factors contributing to elevated radon levels in schools is room depressurization caused by the HVAC system exhausting more air from a room than the supply fan is furnishing to the room. Conversely, if the HVAC system pressurizes the room, radon entry can often be prevented as long as the fan is operating.

Four Maryland schools with varying types of HVAC systems have had mitigation systems installed to reduce elevated levels of indoor radon. Mitigation techniques include depressurization of the area under the slab (sometimes accompanied by the sealing of cracks and holes), and the temporary reduction of radon levels by pressure control through the HVAC system. These systems were effectively reducing radon levels following their installation during the summer of 1988, and fall charcoal canister measurements made in a few of the schools showed continued system effectiveness. The radon levels in these schools are now being monitored to assess system performance during the 1988-89 heating season.

This paper discusses the various school characteristics identified as influencing radon entry, the design and operation of the installed mitigation systems in four schools, and the success of these systems in reducing school radon levels.

INTRODUCTION

In late 1987, radon levels exceeding the Environmental Protection Agency (EPA) guideline of 4 picocuries per liter (pCi/L, 1 pCi/L = 37 Bq/m^3) were identified in several rooms of a school in Fairfax County, VA. This led to extensive radon measurements in schools in Fairfax County in addition to other counties in Virginia and Maryland. More than 30 schools in these counties were visited by the EPA and, based on previous work on radon mitigation in houses, school characteristics that potentially influence radon entry and impact mitigation system design and performance were identified. Mitigation systems were then installed in several of these schools by school personnel with some assistance from the EPA and an experienced radon diagnostician. The details of the mitigation systems installed in four of the Maryland schools are discussed.

Although these schools may not represent the most challenging aspects of school radon mitigation, they do represent the successful application of subslab depressurization, a well-established radon mitigation technique for houses. In addition to subslab depressurization, sealing of suspected radon entry routes and pressure control through the heating, ventilating, and air-conditioning (HVAC) systems were studied in a few of these schools. These mitigation approaches are aimed at preventing radon entry into the schools; consequently, the health concerns associated with exposure to radon daughters are not addressed.

The paper is organized into two parts. Part I summarizes the important characteristics relative to radon entry in schools, and Part II discusses case studies of mitigation systems installed in four schools.

IMPORTANT SCHOOL CHARACTERISTICS RELATIVE TO RADON

To identify and better understand the various characteristics that may influence radon entry into schools and to develop a testing program to efficiently and effectively study various radon control options for schools, more than 30 schools were visited. These schools were inspected in cooperation with the directors of facilities maintenance in Fairfax County in Virginia, and Prince Georges, Montgomery, and Washington counties in Maryland. To confirm, quantify, and develop a better understanding of the characteristics common to schools throughout the U.S., the study will eventually be expanded to characterize a larger number of schools in many geographic areas. It is anticipated that this information will also be applicable to many other similar structures such as office buildings, retail establishments, and public buildings should they require radon mitigation. The information collected thus far has already been useful in providing school districts with guidance on radon-resistant new construction.

If elevated levels of radon are present in the soils beneath a school, characteristics such as HVAC system design and operation, substructure type, building size and configuration, and location of utilities can influence indoor radon levels and consequently impact mitigation system design and performance. The interaction between these characteristics and radon entry and mitigation is discussed below.

HVAC SYSTEMS

The size and complexity of large building HVAC systems is a problem not previously encountered in mitigation of houses. In fact, a significant factor contributing to elevated levels of radon in schools is building or room depressurization caused by the HVAC system. If the HVAC system induces a negative pressure in the building relative to the subslab area, radon in the soil gas can be pulled into the building through floor and wall cracks or other openings in contact with the soil. Similarly, the natural stack effect can also cause radon-containing soil gas to be pulled into the school. If the HVAC system pressurizes the building (a common finding in properly designed and operated systems), it can prevent soil

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gas entry as long as the air-circulating fan is running. However, school HVAC systems are frequently set back or turned off during evenings and weekends, and indoor radon levels can build up during these periods.

In a single-fan system, the air is supplied to the rooms (under pressure) by the air-handling fan, and the return air is pulled back by the same fan. A separate exhaust system may exist or air may exfiltrate due to overpressurization by the supply fan. While operating, a single-fan system can pressurize the school and help reduce radon entry.

Larger air-handling systems often have two fans: a supply fan and a smaller return fan. If the return fan pulls more air from any room than the supply fan is furnishing, the room can be under a negative pressure relative to the subslab area, causing soil gas to enter the room through openings to the soil beneath the slab. Consequently, proper balance is imperative in a two-fan system.

Air-handling systems normally have provision for fresh air intake; however, due to increased energy costs, these systems are not always operated. Older schools sometimes have no mechanical ventilation system. In some schools with either individual unit ventilators in each classroom or with radiant heat systems, ventilation is accomplished only by exhausting air. If the air is exhausted with power fans, the rooms are frequently found to be under significant negative pressure relative to the subslab area, greatly increasing the potential for radon entry. In one of the schools visited that had unit ventilators for HVAC, the fresh air intake in at least one room was open to the soil in the concrete block walls, allowing easy soil gas entry through the unit ventilator.

The air return system can also cause significant depressurization and, consequently, contribute to elevated radon levels. The drop ceiling over the hall, commonly referred to as a plenum, is frequently used for air return with no return ducting. As a result, the entire ceiling plenum is under negative pressure relative to the subslab area. Many of the block walls intersecting the plenum also penetrate the slab and rest on footings under the slab. Radon-containing soil gas under the slab may travel up through the core of the block wall to the return air system in the ceiling plenum and be distributed throughout the building by the air-handling system.

Although most observed return air systems are overhead, a number of systems have air returns under the slab. If the surrounding soil contains elevated radon concentrations, this will create a very difficult mitigation problem, since soil gas will be drawn into the ducts and be distributed throughout the building. Since the discovery of elevated indoor radon levels, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has recommended that where soils contain high concentrations of radon, ventilation practices that place crawl spaces, basements, or underground ductwork below atmospheric pressure be avoided since such practices increase indoor radon concentrations.

SUBSTRUCTURE TYPES AND BUILDING SIZE AND CONFIGURATION

Construction plans of 10 of the slab-on-grade schools—the most prevalent substructure of the schools profiled to date—were examined: all showed aggregate under the slab. As a result, it should be possible to mitigate these schools using subslab depressurization, a radon-reduction technique proven successful in many residences. However, it is anticipated that older schools may not always have aggregate under the slab. Where this is the case, problems will arise for mitigation using subslab depressurization, and other mitigation approaches may be necessary.

Since schools are commonly much larger than houses, they often have interior footings and subslab foundations that can reduce airflow between areas. The location of these subslab barriers will depend on the configuration of the building, and foundation plans should be carefully examined for siting of subslab depressurization points.

OTHER FACTORS INFLUENCING RADON ENTRY INTO SCHOOLS

The location of entry points for utility supply lines can also influence radon entry in schools. Supply line locations depend on many factors such as substructure type, HVAC system, and architectural needs or practices. Utility supply lines located overhead should not cause significant radon entry problems, and overhead is the preferred location as far as radon entry is concerned. However, utility penetrations from the subslab or crawl space area to individual rooms are often not completely sealed, leaving openings between the soil and the building interior. This is commonly the case with sanitary sewer lines, where there is potential for radon entry around the commode ring. In some slab-on-grade schools, the utility lines are located in a subslab utility chase that follows most of the perimeter of the building. The chase has many openings to the soil beneath the slab-on-grade and, consequently, can be a potential radon entry route. Risers to unit ventilators frequently pass through unsealed penetrations in the floor so that soil gas in the utility chase can readily enter the rooms. If the surrounding soil has elevated levels of radon, a utility chase could be a major radon entry route in schools. However, future research will address the possibility of using the utility chase as a radon collection chamber for a subslab depressurization system.

As with houses, floor and wall cracks can also be significant radon entry points in schools. Sometimes these entry routes may be difficult to identify. Carpeting, for example, may conceal cracks in a concrete slab. If the building is under negative pressure, as discussed in the HVAC Systems section, radon can be pulled into the school through these cracks. Fibrous expansion joints that tend to be widely used in school construction can also serve as radon entry routes.

MITIGATION CASE STUDIES IN SCHOOLS

Following the qualitative assessment of school characteristics relevant to radon entry, mitigation systems were installed in several schools in Maryland and Virginia. Case studies of four of these installations follow.

DATA COLLECTION METHODOLOGY

To assist in understanding radon entry into the schools and to design effective mitigation systems for the schools, continuous data were collected as part of the diagnostic measurements. A portable data monitoring system recorded Julian Day, hour, differential pressure (three sensors), and temperature (four sensors). Radon data were collected with a continuous radon monitor (CRM). There was no interface between the CRM and the data logger, and software was developed so that the CRM and data logger data could be merged in a computer for further analysis. Hourly data averages were computed from sensor readings collected approximately every five seconds. This system allows for approximately two weeks of unattended data storage. Not all of the sensors were used during each experiment, and the positioning of sensors varied according to building size and configuration.

In addition to continuous data, five-minute radon grab samples were occasionally collected with the CRM during visits to the schools. Spot pressure differential measurements with a micromanometer were also made in a few cases when set-up of the data logger was not possible. To determine the coverage of subslab depressurization systems, pressure field extension measurements were sometimes made. One-quarter-inch (in, 1 in = 25.4 mm) holes were drilled at various distances and in various directions from the suction holes, depending on building size and configuration, and the resulting test hole pressure measured with a micromanometer. Radon grab samples were occasionally collected through these test holes.

CASE STUDY A: PRINCE GEORGES COUNTY, MD

Radon levels in this school were initially measured in February 1988 with charcoal canisters: one classroom tested above 40 pCi/L, a teachers' lounge tested above 20 pCi/L, and several other classrooms tested between 4 and 20 pCi/L. The building is slab-on-grade construction with a large two-fan air-handling system. The HVAC system had a rated capacity of 51,000 cfm (1 cfm = 0.47 L/s) of air supply and 34,000 cfm of return air. Louvers regulate the amount of fresh air and recycled air in the system. This would result in positive pressure in all rooms if the system were properly balanced. However, continuous radon and pressure measurements indicated that many of the rooms were under negative pressure relative to the subslab area when both the supply and return fans were in operation. As seen in Figure 1, there was a good correlation in all rooms between negative pressure (in the room relative to the hallway) and radon, with the highest radon levels in the rooms with the highest negative pressures.

The room with the highest radon level (usually 10 to 20 pCi/L) typically measured between 0.06 in and 0.08 in negative pressure relative to the subslab. When the return air fan was turned off, the pressure in the room became positive, and radon levels decreased to less than 2 pCi/L. Examination of the air-handling system showed that the air supply fan had been damaged, resulting in a significant capacity loss. As a result, the supply fan was actually supplying less air than the return air fan was removing, causing a negative pressure in many rooms.

This same room with the highest radon level and the highest negative pressure also had a very large floor-to-wall crack along one wall. This particular crack was an expansion joint where two parts of the building were joined. The material in the expansion joint had disintegrated, and the parts appeared to have separated, leaving a 1-in gap between the floor and wall. This gap was concealed by an aluminum angle iron installed when the building was built. When the return fan was operating, initial tests in this room showed a large flow of radon-containing soil gas out of this crack. The radon level was about 500 pCi/L in the soil gas entering the room through the crack, the same measured under the slab in the middle of the room. When the return air fan was turned off and the room was pressurized by the air supply fan, room air flowed into the crack and consequently no soil gas was entering. The pressure in the room relative to the subslab increased to about 0.01 in, and radon levels in the room quickly dropped below 2 pCi/L. The floor-to-wall crack was sealed with backer rod and urethane caulking. This sealing decreased radon levels only slightly when both fans were off, indicating other soil gas entry points in the room.

The influence of HVAC operation on the pressure differential between this room and the subslab area and the resulting radon levels in the room are displayed in Figure 2 for a seven-day period. (The return air louvers were closed during these measurements.) While the HVAC system is operating, the room is at a higher pressure than the subslab area and, consequently, radon entry is reduced. However, when the HVAC system is turned off during night and weekend setback, pressure in the room becomes negative relative to the subslab area and radon levels increase.

As a temporary solution to reduce radon levels, the return air fan was left off and the HVAC system operated with only the air supply fan. Under these conditions, all rooms showed positive pressure and had radon levels below 2 pCi/L during HVAC operation. The damaged supply fan has now been replaced and the air supply and air return systems are being balanced.

As a precaution to reduce radon entry when the air handlers are not operating during night or weekend setback, two fan-assisted subslab depressurization points have been installed. It is anticipated that this will be an effective mitigation system since the school was constructed on 4 in of subslab aggregate. Follow-up testing was initiated during the 1988-89 heating season.

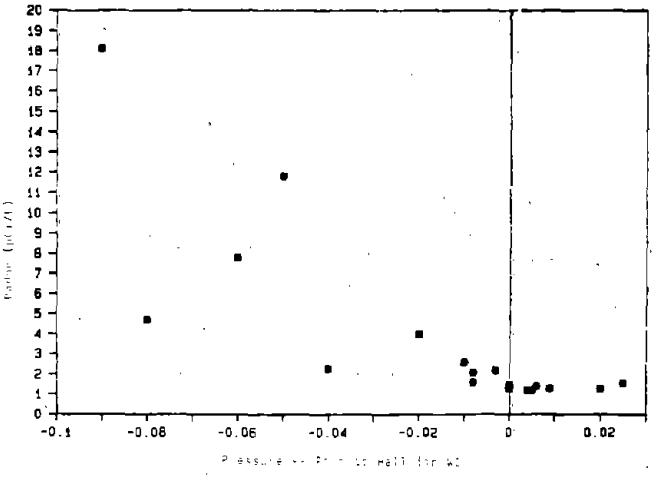

Figure 1 Correlation between room pressure—relative to hall—and radon level (Case Study A)

CASE STUDY B: WASHINGTON COUNTY, MD

This is a small school built on the side of a hill with a walkout basement along the lower side. The unexcavated area is slab-on-grade with the slab extending over the basement area and resting on steel bar joists. The foundation walls are concrete block. The interior wall of the basement supports the end of the bar joists and the slab. This wall is not painted or waterproofed on either side. Building plans specify 4 in of subslab aggregate.

The HVAC system consists of a single-fan system on each floor. A fresh air intake into the return air duct is under negative pressure during fan operation. Pressure measurements indicate that the building is under positive pressure even when the fresh air intake is set for minimum supply. However, since the HVAC system is normally set to run only when heating or cooling is required, the system may not operate during mild weather. In addition, the temperature in the below-grade part of the school is often buffered and, consequently, the basement HVAC system does not run as often as the upstairs system.

Radon levels in all rooms were measured with charcoal canisters over a weekend in May 1988 with air handlers off. Measurements ranged from 78 to 82 pCi/L in the basement and from 18 to 33 pCi/L on the first floor. Subslab and block wall grab samples measured as high as 1500 pCi/L.

Continuous radon measurements were made on both floors of the school during all phases of mitigation. Before mitigation, radon levels rose dramatically at night if the air handlers were off but did not rise during continuous operation. Pressure measurements indicated that operation of the air handlers produced a slight positive pressure in the building relative to the subslab area, thus reducing soil gas entry. In the hottest part of the summer, radon levels rose dramatically overnight when the air handlers were off. It is suspected that a night stack effect resulted since the hot inside daytime temperatures did not decrease as rapidly at night as the outdoor temperature. Overnight levels as high as 150 pCi/L were reached in the basement and levels as high as 100 pCi/L were reached on the first floor when the air-handling fans were off during hot weather. Continuous operation of the HVAC reduced radon levels to less than 4 pCi/L within an hour.

As a temporary solution, the HVAC system was run continuously while the school was occupied. For a permanent solution, subslab depressurization points were installed in phases in both the basement and on the first floor. Due to the high radon levels and complex foundation, it was anticipated that several suction points would be needed.

A 1-ft-diameter (0.305 m) subslab suction pit was installed in the basement with a 4-in-diameter pipe, and radon reduction was about 50% with the subslab pressure field extending less than 30 ft. The suction pit was excavated further to a diameter of about 3 ft with an additional decrease in radon levels and an increase in pressure field extension. The suction fan was replaced with a larger fan, resulting in additional reductions in radon levels. This also increased pressure field extension to 40 ft. This basement suction point also caused some measurable depressurization under the first floor slab, indicating some communication between the slabs.

To evaluate the effectiveness of the single-point subslab suction system in this school and to investigate the effects of the single-fan HVAC system on mitigation performance, Figure 3 shows radon and pressure measurements in the school over a 10-day period. The first-floor single-fan HVAC system was operated continuously during the school week to reduce radon levels while the school was in session on the first floor. Since the basement was unoccupied during the monitoring period, the basement HVAC system was not operated. Over the weekend (day 156), the HVAC system and the single-

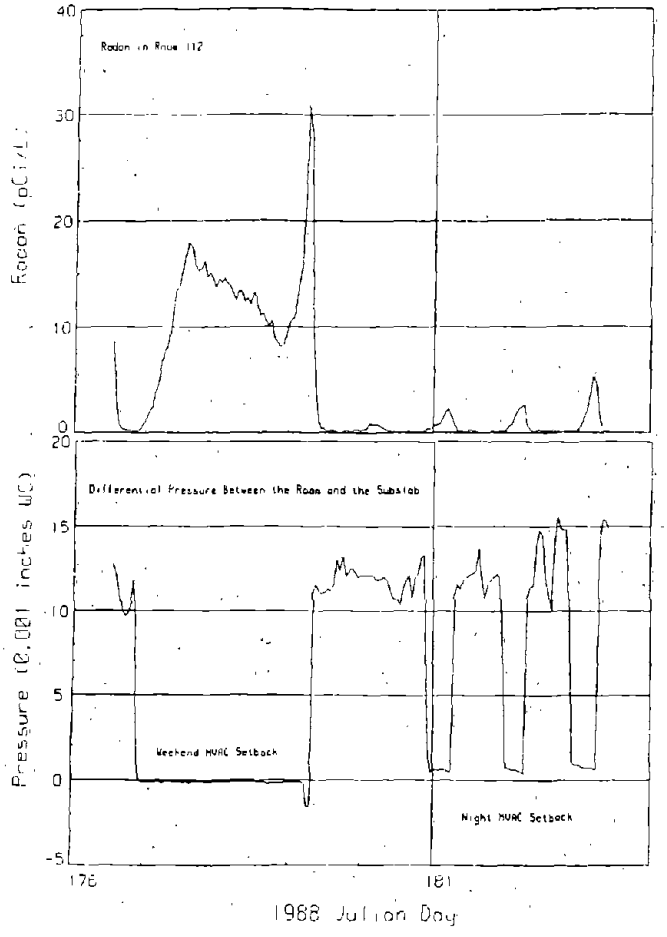

Figure 2 Influence of HVAC operation on radon levels (Case Study A)

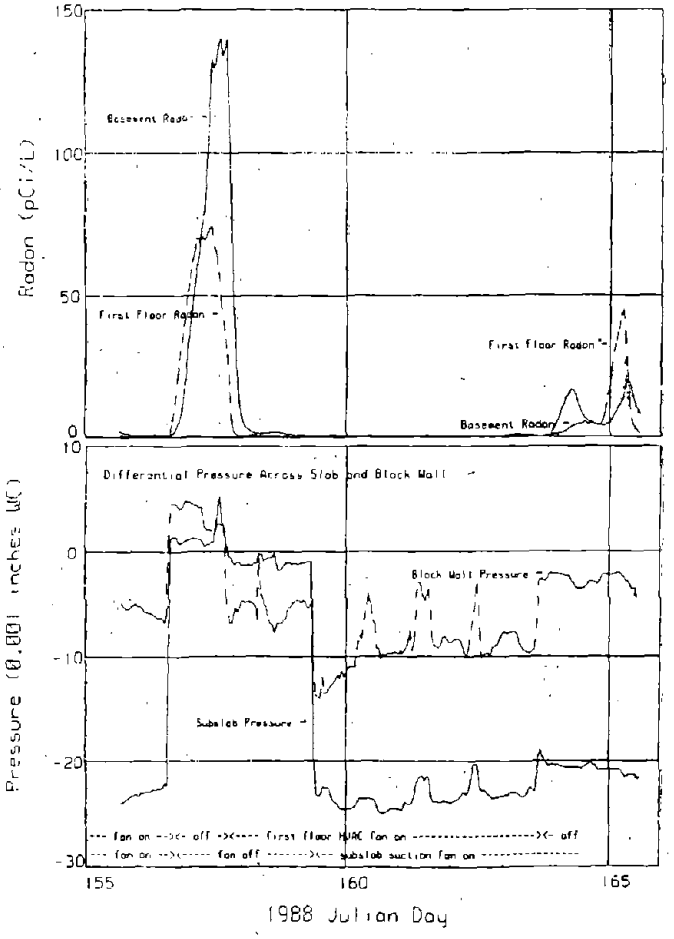

Figure 3 Influence of HVAC operation and single-point subslab depressurization on radon levels and pressure (Case Study B)

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point subslab suction system on the first floor were turned off, and the radon levels rose quickly to more than 70 pCi/L on the first floor and 140 pCi/L in the basement. On day 157 the subslab suction system remained off, but the first-floor HVAC system was turned on. Radon levels on both floors dropped, and the differential pressure under the slab and within the block wall became slightly negative relative to the room. On days 158-163, both the HVAC system and subslab suction system were operating, and radon levels remained low. On days 164 and 165, the subslab suction system was operated and the first-floor HVAC system was off. This resulted in an increase of first-floor radon levels to 40 pCi/L, indicating that one suction point was not adequate if the HVAC system was not operating.

To ensure acceptable radon levels on the first floor while the HVAC system was not in operation, another suction point with a 3-ft-diameter suction pit was installed on the first floor. Addition of this suction point reduced levels on the first floor although radon levels on both floors still rose above 10 pCi/L at night with the HVAC system off.

Pressure field extension measurements made with these two suction points operating indicated incomplete coverage of both floors. Consequently, two additional suction points with 1-ft-diameter suction pits were installed in the basement, and a fifth suction point with a 1-ft-diameter suction pit was installed on the first floor.

Nine pressure field extension measurements showed overlapping fields between suction points in the basement area, indicating that all of the basement subslab was adequately depressurized. Basement radon levels measured less than 2 pCi/L with the air handlers off and the mitigation systems operating; however, first-floor radon levels still rose above 4 pCi/L at night with the air handlers off.

Based on mapping of subslab radon levels in more than 20 test holes on the first floor, three additional suction points were installed, each with a 6-in-diameter pipe and a 1-ft-diameter subslab suction pit. Two points were manifolded to a single fan, and a separate fan was installed on the other suction point. After installation of these last three suction points, radon levels stayed below 4 pCi/L on both floors, except for occasional brief excursions at night. A larger fan was installed, and this appears to be reducing radon levels satisfactorily. More than 10 pressure field extension measurements made on the first floor showed little variation in the short-term when the first-floor HVAC system was turned off. This indicates that the present system is achieving adequate coverage even when the HVAC fan is not operating.

Although subslab suction was effective in solving a serious radon problem at this school, it was surprising that it took eight suction points. Aggregate under the slab was confirmed visually at every suction point; however, the aggregate used was probably unscreened "crusher run" containing a great deal of fines. This tends to confirm the belief that screened, coarse aggregate (3/4 to 1 1/4 in), essentially free of any material less than 1/4 in diameter, is preferred for optimal operation of subslab depressurization systems.

CASE STUDY C: WASHINGTON COUNTY, MD

This entire school building is slab-on-grade with block walls and no utilities below grade except sanitary sewers. The original building was constructed in 1956 and has four area air handlers for heating and ventilating with a central boiler room. A classroom wing was added in 1968 and unit ventilators are in each room. None of the building is air-conditioned. Construction plans specified 4 in of subslab aggregate under the entire building. Elevated radon levels were found in the locker rooms on each side of the gymnasium in the original building and in the new classroom wing. Mitigation of each of these areas is discussed separately.

Original Building—Locker Room Mitigation

Although the locker rooms and gymnasium are on the same air handler, the gymnasium measured 2 pCi/L; the girls' locker room, 5 to 6 pCi/L; and the boys' locker room, 5 to 19 pCi/L. Further examination indicated that each locker room area had large exhaust fans to remove odors and shower steam. Differential pressure measurements (using a micromanometer) with the air handler and exhaust fans operating correlated with the radon levels showing that the gymnasium was slightly positive, the girls' locker room area slightly negative, and the boys' locker room area significantly negative.

Construction plans showed that each locker room area was a continuous slab over aggregate. As a result, a subslab suction point, using a 6-in pipe, was placed in each locker room area with a 1-ft-diameter suction pit. Both locker room areas measured less than 4 pCi/L with the exhaust fans and the subslab depressurization systems operating, indicating that the subslab suction systems effectively overcame the negative pressures caused by the exhaust fans.

New Classroom Wing

Weekend charcoal canister measurements were made in April 1988 in this wing with the unit ventilators off. All but one room measured above 4 pCi/L: a room in the northeast corner measured 27 pCi/L. Levels decreased from north to south in this wing, as did subslab radon levels. A CRM was placed in the room with the highest radon levels. When the unit ventilator was off, levels above 20 pCi/L were reached nightly but remained below 2 pCi/L when the unit ventilator was run continuously. Pressure measurements with a micromanometer confirmed that the unit ventilator was pressurizing the room slightly.

Since the unit ventilators are off at night (except in extremely cold weather, when they are cycled), it was decided to install two subslab depressurization points in the wing. These 4-in suction pipes were installed in the hall and manifolded with an above-ceiling 6-in pipe running to a fan at the north end of the building. One suction point was installed with a 3-ft-diameter suction pit about 20 ft from the east end of the hall and the other suction point was installed with a 1-ft-diameter suction pit about 40 ft west of the first point. Pressure field extension measurements indicated that the two fields overlapped, and all of the wing was depressurized to the outside walls except for the southernmost classrooms.

Since the pressure field extension around the 1-ft-diameter suction pit was not as great as around the 3-ft-diameter suction pit, the 1-ft-diameter suction pit was increased to 3 ft in diameter. This extended the measurable depressurization area by 10 ft to the south (enough to reach the last two classrooms) and about doubled the amount of depressurization in the test holes in all directions around the suction point. With the subslab depressurization system operating and the unit ventilator fans off, radon levels were less than 4 pCi/L in all classrooms.

CASE STUDY D: WASHINGTON COUNTY, MD

The original building of this school was built in 1958 and is heated with hot water radiant heat in the slab. In 1978 a kindergarten room was added to the original building, and a separate building (referred to as Building B) was built, con-

taining four classrooms, a library, a teachers' workroom, a conference room, and restrooms. The kindergarten room is heated with hot water radiant heat, and the new building is heated with unit ventilators. Office space in the original building is air-conditioned with a window unit. No other area of either building is air-conditioned.

The original building has two 3600-cfm roof-mounted fans that could be used to exhaust air in plenums over the hall ceiling. Each room has a ceiling vent connecting to these hall plenums. However, the exhaust fans are never used. Consequently, the building has no active ventilation system. Plans showed that the original building had 6 in of aggregate under a 6-in-thick slab (containing hot water pipes) and Building B had 4 in of aggregate under a 4-in slab.

All rooms in both buildings were tested with charcoal canisters over a weekend in mid-April 1988. The eight rooms in Building B measured between 17 and 20 pCi/L. It is believed that the unit ventilators were off during the testing weekend, but this could not be confirmed. Seven tests in the classrooms, library, and multi-purpose room in the original building measured between 12 and 23 pCi/L. Mitigation of the two buildings is discussed separately.

Building B (Unit Ventilators)

A CRM was placed in one of the classrooms in Building B to measure the effects of unit ventilator operation on radon entry. It was found that radon levels would rise overnight to more than 20 pCi/L with the ventilator off but would remain below 2 pCi/L with the ventilators on. Again, this shows that this type of ventilator can pressurize the room slightly, preventing radon entry when run continuously.

Since the ventilators are off during night setback, a four-point subslab depressurization system was installed. Four 4-in-diameter pipes were connected to two 6-in manifold pipes above the drop ceiling with a common suction fan. (Two vertical pipes are manifolded to each overhead pipe.) Pressure field extension measurements indicated that depressurization extended 50 ft, the minimum distance necessary to reach all parts of the slab.

With the subslab system operating and the unit ventilators off, all rooms remained below 4 pCi/L. However, based on the pressure field extension measurements, the system may be marginal during cold weather. If radon levels rise above 4 pCi/L, it is believed that subslab depressurization can be improved by sealing the floor-to-wall opening. (One-half-in expansion joints around all of the slabs in the building are deteriorating, leaving significant openings to the subslab. This probably leads to some short-circuiting of the subslab depressurization system.)

Original Building (Intra-Slab Radiant Heat)

Subslab suction on this intra-slab radiant-heated building was a challenge since construction plans showed that the hot water pipes in the slab were 15 in or less apart over the entire building. As a result, it was difficult to locate an area where a 6-in subslab suction point could be placed without damaging a hot water pipe. A 3-ft-square area without water pipes was finally located in each room. A hole was successfully cut through one of these areas. The plans indicated that the aggregate was a minimum of 6 in deep, much deeper than at any other school examined. A 6-in-diameter suction pipe was installed with a 3-ft-diameter pit. Pressure field extension was far greater than expected, and depressurization could be measured as far as 90 ft from the suction hole. These results were surprising since the aggregate appeared to be some type of "crusher run" aggregate with a certain amount of fines. However, in leveling the aggregate before pouring the concrete, it is probable that most of the fines had sifted to the lower portion of the aggregate bed, leaving a fairly thick area of large-diameter aggregate immediately under the concrete. It is believed that this layer of coarse stone made for a much greater pressure field extension and will be studied further. Preliminary follow-up tests indicate that this one suction point will solve the radon problem in the original building.

To analyze the effectiveness of a single-point subslab suction system and to investigate the pressures that control radon levels in schools during hot weather, radon, pressure, and temperature were monitored continuously in one classroom, as shown in Figure 4. The classrooms were kept closed during this period of very hot weather, and there is no ventilation system in this building. When the subslab suction system was turned off from day 222 through day 225, the radon levels quickly rose and followed a diurnal cycle that seems to match the temperature cycle. When the outdoor temperature was coolest relative to indoor temperature, the radon levels were highest. This can be expected from the stack effect, as discussed in Case Study B. Although a small positive pressure was measured across the slab during this period, it does not show significant diurnal variation. The differential pressure across an outside classroom wall does not show much correlation with the radon levels, except for a sharp dip in the middle of day 224 that may be due to wind.

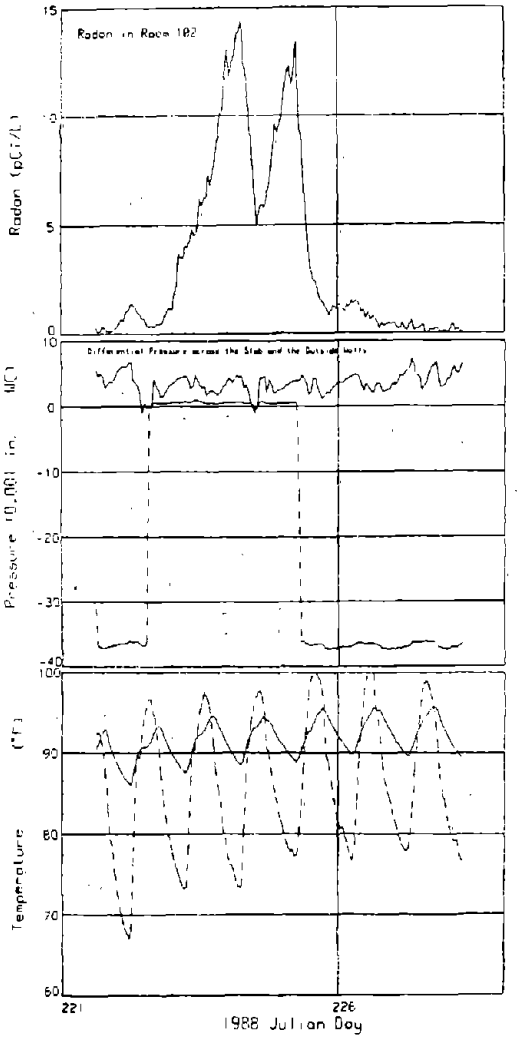

Figure 4 Effect of single-point subslab depressurization on radon levels (Case Study D)

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Kindergarten Room

Since the kindergarten room is an addition, the subslab area does not communicate with the original building. Consequently, a suction point was put in a closet adjacent to a restroom where the hot water pipes were spaced 24 in apart to clear the sewer line of the commode. This suction point lowered radon levels to less than 2 pCi/L. No pressure field extension measurements were made for fear of damaging a heating water pipe.

CONCLUSIONS

The following tentative conclusions can be drawn from the EPA's experience in assisting in the installation of radon mitigation systems in Maryland schools. These tentative conclusions are based on limited studies and will be verified and expanded with further research.

1. One of the most significant factors contributing to elevated levels of radon in schools and influencing the mitigation approach is the design and operation of the HVAC system. The complexities of large building HVAC systems present problems not previously encountered in house mitigation.
2. Pressure control through continuous HVAC fan operation can often be an effective temporary solution to reduce elevated radon levels in schools, depending on HVAC system design. Whether such a technique is a feasible long-term solution depends on factors such as the proper operation of the system by maintenance personnel, variations in outside environmental conditions, and any additional maintainance costs and energy penalties associated with increased operation of the HVAC system.
3. A subslab depressurization system can usually overcome negative pressures induced by HVAC operation in schools if there are no return air ducts under the slabs. As with houses, subslab depressurization is more successful (and requires fewer suction points) when the slab is poured over clean, coarse aggregate.
4. Effective mitigation of schools using subslab depressurization requires greater fan capacities and suction pipe diameters than does mitigation of houses. The capacities of the fans used in these school installations were typically at least 300 cfm (at 0.75 in WC) compared to capacities of about 150 cfm (at 0.75 in WC) for fans commonly installed in house subslab depressurization systems. Suction pipe diameters of 4 in to 6 in often proved successful in these installations, compared to pipe diameters of 4 in or less typically used in houses.

ACKNOWLEDGMENTS

We would like to thank all the school personnel who contributed to the information presented in this paper.

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DISCUSSION

Carl N. Lawson, LRW Engineers, Tampa, FL: In any of your school work, have you studied any multi-level projects? If so, what were the results?

K.W. Leovic, U.S. EPA, Research Triangle Park, NC: The only multi-level school we studied was a basement/slab-on-grade school (where the basement was used for classroom space). This is in case study B.

We have not yet studied any other multi-level schools. Controlling radon entry at the lowest level in contact with the soil—and ensuring that the HVAC system does not distribute radon to upper levels—will probably be the best approach.

Marian Heyman, Hartford Steam Boiler Inspection and Insurance Co., Hartford, CT: Are there any guidelines and/or recommendations for testing floors higher than basement/first floors for radon in schools? The question is asked in light of recommendations to test the second floor of homes, especially homes using wellwater. Radon aerosolized through water taps and showerheads can contribute significantly to radon concentrations in a home. Can any of this information be applied in schools?

Leovic: Current EPA guidelines, "Radon Measurements in Schools—An Interim Report," recommend that measurements be made in all rooms frequently used on or below the grade level. Since schools tend to use public water supplies, rather than private wells, radon in water will probably be less applicable in schools than in residential housing.

DESIGN FOR INTEGRATED IAQ/THERMAL COMFORT ZONING

Milton Meckler, P.E.
ASHRAE Fellow

ABSTRACT

HVAC systems now function to provide an environment where temperature, air distribution, and humidity are maintained within prescribed operating ranges. The purpose of this paper will be to describe a simplified design approach to zoning for indoor air quality as well, so that all critical environmental factors are jointly considered.

The proposed ASHRAE Standard 62-1981R, "Ventilation for Acceptable Indoor Air Quality," provides criteria for the application of the Indoor Air Quality (IAQ) procedure as an alternative to the more prescriptive Ventilation Rate Procedure (VRP). Table 1, used in conjunction with the IAQ procedure, defines seven classes of air distribution systems which relate filter locations in terms of space concentration of contaminants and required outdoor and recirculation air rates.

By the use of the IAQ procedure, four case studies of alternative occupancies within a nominal 22,000 ft² office building will be presented. These studies include various scenarios of adjacent leased spaces of varying occupancy to demonstrate the application of the newly proposed integrated IAQ/thermal comfort zoning design procedure developed to allow health matters to be adequately addressed when zoning is first established by HVAC designers. Use of lead/lag and best use of combining multiple rooms within a common IAQ/thermal comfort zone will also be explored.

INTRODUCTION

In recent years, engineering professionals designing heating, ventilating, and air-conditioning (HVAC) systems are more and more being held accountable for the health and safety of the occupants of the buildings served by those systems. This is, perhaps, a direct result of an increased public awareness of the health and safety risks associated with some uncontrolled contaminants and a growing awareness within the general public that their health may be at risk. Although energy efficiency is a necessary criterion for good engineering design, it must not be allowed to overshadow valid environmental concerns for occupant well-being and protection against undue discomfort, sickness, and loss of productive time.

HVAC systems must function to provide an environment where all four of the following factors are maintained within prescribed operating ranges/levels, namely: temperature, air distribution, humidity, and air quality. A general consensus already exists within ASHRAE with regard to the first three parameters. Unless a case can be made for air quality zoning, the resulting air distribution design approach generally becomes a function of temperature and/or humidity (i.e., comfort) considerations only. It will be shown that not only is IAQ zoning necessary but it can be easily facilitated using the alternative IAQ procedure inherent in the proposed ASHRAE Standard 62-1981R.

Most documented cases of "sick-building syndrome" (SBS) or "building-related illness" (BRI) reflect a failure to diagnose and/or relate occupant discomfort or illness with building operations. Unless corrective action is taken promptly, widespread hysteria, dissatisfaction, and loss of morale can spread, leaving the way open to third-party suits. It is the responsibility of the HVAC system designer to select systems capable of satisfying occupant IAQ needs by keeping known indoor air contaminants and energy consumption within acceptable limits.

SBS or BRI generally refer to a class of build-up with potential health problems where construction materials (and often maintenance chemicals) combine with poor ventilation and air circulation, resulting in inadequate amounts of treated outdoor and recirculated air being supplied to the building inhabitants.

Symptoms range from headaches, nausea, eye strain, dizziness, rashes, persistent cough, dry throat, and some respiratory problems varying in degrees. Sources reported in the literature include environmental tobacco smoke (ETS) (Collett et al. 1988), formaldehyde (widely used in furniture and building materials), plasticizers, paint, wall and ceiling materials, cleaning agents (e.g., rug shampoos), fiberglass and mineral wool, carbon monoxide, carbon dioxide, adhesives, caulking, pesticides, various viable and non-viable microorganisms (e.g., often found to be growing in ductwork and/or in standing water or on cooling coils of air-conditioning equipment), and various other volatile organic compounds (VOC) (e.g., copy machine chemicals, etc.) (Morey and Robertson 1988).

IAQ is directly related to outdoor air quality because ventilation employing outdoor air is essential to replace the oxygen consumed as well as to dilute indoor air pollutants to an acceptable level. For example, carbon dioxide exhaled by occupants must be diluted to achieve desirable comfort as well as to reduce odors and avoid serious health hazards. As the ventilation load increases, the amount of outdoor air needed to dilute occupant-generated carbon dioxide increases.

Proposed ASHRAE Standard 62-1981R recommends 15 cfm of outdoor air per person as the minimum needed to control occupant odors and guarantee that the concentration of carbon dioxide will not exceed 1000 ppm. It also recommends that the indoor air as a minimum should not exceed limits currently established by the Environmental Protection Agency (EPA) for outdoor air and collectively known as the National Primary Ambient Air Quality Standards (NPAAQS).

The EPA has mandated that the concentration of particulates should not exceed 50 $\mu g/m^3$ and 150 $\mu g/m^3$, for long and short terms, respectively (refer to Table 2). The *Air Quality Standards Compliance Report*, published monthly by the South Coast Air Quality Management District (SCAQMD) in southern California, compares outdoor air quality by means of readings taken at several designated air-monitoring

TABLE 1

Effect of Filter Location and System Parameters on Required Outdoor Air, Space Contaminant Concentration or Recirculation Rate

Class	Filter Location	Required Recirculation Rate: Flow	Temperature	Outdoor Air	Required Outdoor Air	Space Contaminant Concentration	Required Recirculation Rate
I	None	VAV	Constant	100%	$V_o = \frac{N}{E_v F_r (C_s - C_o)}$	$C_s = C_o + \frac{N}{E_v F_r V_o}$	Not applicable
II	A	Constant	Variable	Constant	$V_o = \frac{N - E_v RV_r E_r C_s}{E_v (C_s - C_o)}$	$C_s = \frac{N + E_v V_o C_o}{E_v (V_o + RV_r E_r)}$	$RV_r = \frac{N + E_v V_o (C_o - C_s)}{E_v E_r C_s}$
III	A	VAV	Constant	Constant	$V_o = \frac{N - E_v F_r RV_r E_r C_s}{E_v (C_s - C_o)}$	$C_s = \frac{N + E_v V_o C_o}{E_v (V_o + F_r RV_r E_r)}$	$RV_r = \frac{N + E_v V_o (C_o - C_s)}{E_v F_r E_r C_s}$
IV	A	VAV	Constant	Proportional	$V_o = \frac{N - E_v F_r RV_r E_r C_s}{E_v F_r (C_s - C_o)}$	$C_s = \frac{N + E_v F_r V_o C_o}{F_r E_v (V_o + RV_r E_r)}$	$RV_r = \frac{N + E_v F_r V_o (C_o - C_s)}{E_v F_r E_r C_s}$
V	B	Constant	Variable	Constant	$V_o = \frac{N - E_v RV_r E_r C_s}{E_v [C_s - (1 - E_r) C_o]}$	$C_s = \frac{N + E_v V_o (1 - E_r) C_o}{E_v (V_o + RV_r E_r)}$	$RV_r = \frac{N + E_v V_o [(1 - E_r) C_o - C_s]}{E_v E_r C_s}$
VI	B	VAV	Constant	Constant	$V_o = \frac{N - E_v F_r RV_r E_r C_s}{E_v [C_s - (1 - E_r) C_o]}$	$C_s = \frac{N + E_v V_o (1 - E_r) C_o}{E_v (V_o + F_r RV_r E_r)}$	$RV_r = \frac{N + E_v V_o [(1 - E_r) C_o - C_s]}{E_v F_r E_r C_s}$
VII	B	VAV	Constant	Proportional	$V_o = \frac{N - E_v F_r RV_r E_r C_s}{E_v F_r [C_s - (1 - E_r)(C_o)]}$	$C_s = \frac{N + E_v F_r V_o (1 - E_r) C_o}{E_v F_r (V_o + RV_r E_r)}$	$RV_r = \frac{N + E_v F_r V_o [(1 - E_r) C_o - C_s]}{E_v F_r E_r C_s}$

TABLE 2

National Primary Ambient Air Quality Standards Set by Environmental Protection Agency for Outdoor Air

Air Pollutant	Long Term: Concentration µg/m³	Long Term: Concentration ppm	Long Term: Average	Short Term: Concentration µg/m³	Short Term: Concentration ppm	Short Term: Average
Sulfur Dioxide	80.0	0.030	1 Year	365(a)	0.14(a)	24 Hours
Particles (PM 10)	50.0(b)	—	1 Year	150(a)	—	24 Hours
Carbon Monoxide	—	—	—	40,000	35.00	1 Hour
Carbon Monoxide	—	—	—	10,000(a)	9.00(a)	8 Hours
Oxidants (Ozone)	—	—	—	235(c)	0.12(c)	1 Hour
Nitrogen Dioxide	100.0	0.055	1 Year	—	—	—
Lead	1.5	—	3 Months(d)	—	—	—

(a) May be exceeded only once per year.
(b) Arithmetic mean.
(c) Standard is attained when expected number of days per calendar year with maximum hourly average concentrations above 0.12 ppm (235 µg/m³) is equal to or less than 1.
(d) 3-month period is a calendar quarter.

REFERENCE: Proposed ASHRAE standard 62-1981R.

stations in the South Coast Air Basin and Southeast Desert Air Basin to the state and federal ambient air quality standards. This report, compiled over a six-month period (January 1988 through June 1988) indicated that the concentration of particulates alone recorded in a 24-hour period in the outdoor air exceeded both state and federal standards in 1987 (SCAQMD 1988). For example, Figure 1 shows that particulate levels in the respirable range (PM 10) for the month of February 1988 exceeded both state and federal standards by far in comparison to others. Therefore, use of outdoor air in Los Angeles as a dilution strategy for particulates became highly questionable.

Since proposed ASHRAE Standard 62-1981R requires that the indoor air not exceed the above-referenced NPAAQS standards in designing for all areas within the SCAQM district, it may be prudent to consider measures that reduce the introduction of particulates in the respirable range (i.e., PM 10) since they are known to be potentially harmful to human health (Meckler 1984, 1985). The use of air recirculation in conjunction with proper filtration and air cleaning may provide a more viable alternative for particulate control in buildings located within the SCAQMD as well as offering

TABLE 3

Calculated Load Summary and Volumetric Air Flow Rates in Each Zone of Office Building in Burbank, California

Zone	Zone Area (FT^2)	Room Sen. Load (BTU/HR)	*No. of People	Room Latent Load (BTU/HR)	Room Total Load (BTU/HR)	Supply Air (CFM)
Telecommunications	5,000	280	300	57	337	12,740
Conference Rooms	4,000	164	200	50	214	7,600
Offices	9,000	281	63	12	293	13,000
Shops	4,000	147	100	25	172	6,800

*Based on revised ASHRAE standard 62-1981R

the potential to reduce the associated energy cost of having to clean and condition excess (i.e., dilution) outdoor air.

The proposed IAQ procedure is an integral part of ASHRAE Standard 62-1981R and can be used to compute the amount of outdoor air required for known amounts of indoor air contaminants. Equations are presented for the more commonly used air distribution systems, as shown in Table 1. Referring to Table 1, one needs only specify the following parameters to establish compliance: indoor contaminant level, C_s; outdoor contaminant level, C_o; filter effectiveness, E_f; ventilation effectiveness, E_v; flow reduction factor, F_r; return rate, V_r; and the contaminant generation rate, N, of concern.

For purposes of illustration only, we are now going to assume that for buildings in the SCAQM district, particulates represent the contaminant of greatest concern at present for reasons given above. Accordingly, the following examples, while directed principally toward meeting acceptable short-term particulate levels in compliance with NPAAQS, could just as easily be used to examine any other contaminant of

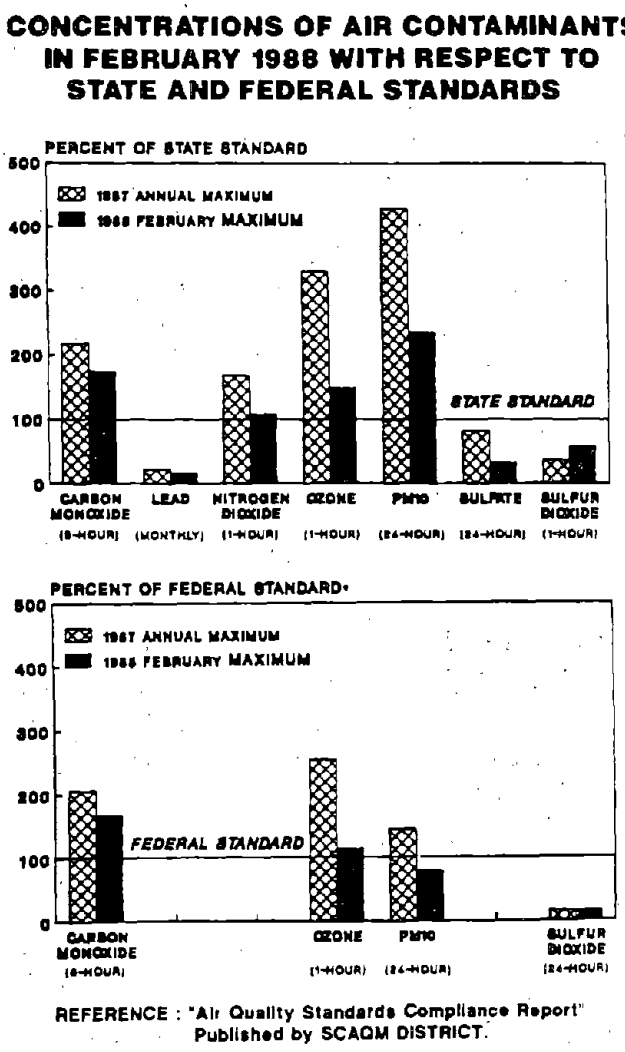

Figure 1 *Concentrations of air contaminants in February 1988 with respect to state and federal standards*

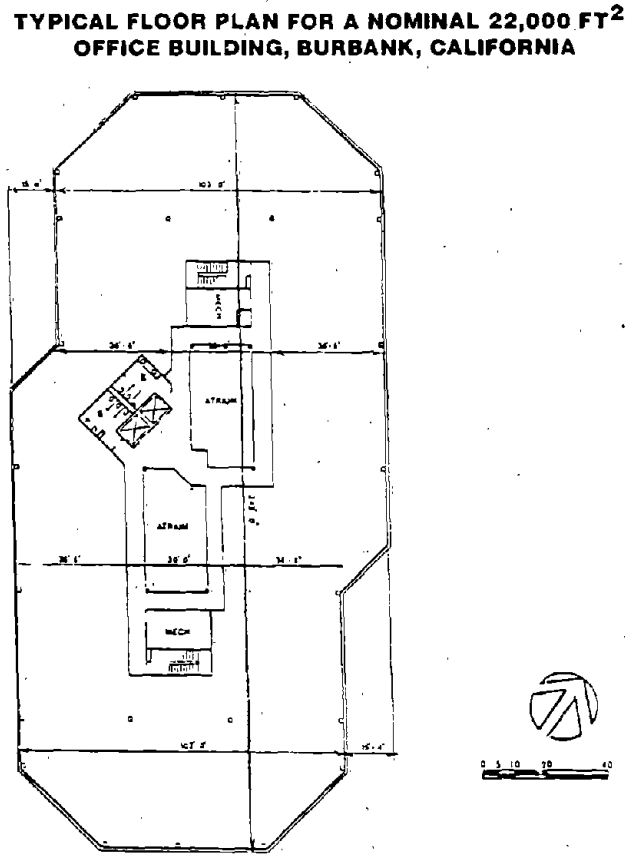

Figure 2 *Typical floor plan for a nominal 22,000 ft² office building, Burbank, CA*

interest. Therefore, there is a present need to develop a consistent methodology that can be used to evaluate how best to zone for IAQ (i.e., health needs) as well as temperature and humidity (i.e., comfort needs). The case studies that follow are offered to illustrate examples of how the proposed IAQ zoning procedure can be implemented.

Employing the equations presented in Table 1, we programmed our computers to solve directly for C_s, V_o, and simultaneously verified all flow balances (i.e., to and from the conditioned spaces of interest). Case studies using the above-described computer procedure are as follows.

CASE STUDIES

The following examples illustrate the computer-assisted (Meckler 1986) use of IAQ procedure by the use of equations presented in Table 1 for variable-air-volume (VAV) systems at 100% full- and 50% part-load conditions. The 50% part-load condition is assumed to be a minimum to provide acceptable indoor contaminant levels. Also notice that number of people in a zone and $\dot{N}$ are reduced to realistically reflect the reduced activities at 50% part-load conditions. The building under study is a nominal 22,000 ft² office building in Burbank, CA, and its dimensions are given in Figure 2. It contains four separate occupancy zones: a) telecommunications, b) conference rooms, c) offices, and d) shops. The calculated load summary in Table 3 shows square footage of each zone, individual zone loads, number of people present in each zone, and volumetric flow rate of air supply in cfm.

Following are four cases studying various VAV system configurations:

(1) Case 1, conventional VAV system (Class VI)
(2) Case 2, conventional VAV system (Class VII)
(3) Case 3, modified water source heat pump (WSHP)/packaged terminal air conditioner (PTAC) system (Class VI)
(4) Case 4, integrated desiccant cold air distribution (IDCAD) system

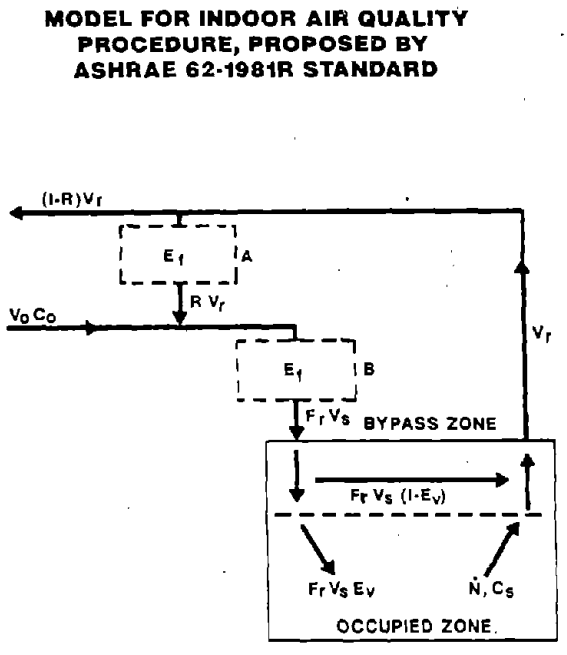

Figure 3 Model for indoor air quality procedure, proposed by ASHRAE Standard 62-1981R

Case 1. Conventional VAV System (Class VI in Table 1)

The following data are for the telecommunications zone. At 100% full-load condition, the system parameters are:

Volume of space = 1133 m³ (40,000 ft³)
Number of people = 300
$\dot{N}$ = 15 μg/min·m³ (based on ASHRAE Standard 62-1981R)
E_v = 0.8 (based on reported test results for air distribution)
V_s = 361 m³/min (12,740 cfm)
E_f = 0.5
F_r = 1.0
C_o = 5 μg/m³

At 50% part-load condition, the system parameters are:

Volume of space = 1133 m³ (40,000 ft³)
Number of people = 210
$\dot{N}$ = 10.5 μg/min·m³ (based on ASHRAE Standard 62-1981R)
E_v = 0.8 (based on reported test results for air distribution)
V_s = 361 m³/min (12,740 cfm)
E_f = 0.5
F_r = 0.5
C_o = 5 μg/m³

The mass balance equation for V_o in Table 1 and the flow balance equation of $V_o = F_rV_s - RV_r$ in Figure 3 are simultaneously solved. To satisfy the condition of $C_s < 50$ μg/m³ and $C_s < 150$ μg/m³ at long and short terms, respectively, and a minimum outside supply air of 15 cfm/person (revised ASHRAE Standard 62-1981R), at part as well as full loads, V_o is found to be 4358 cfm with C_s = 89 μg/m³ at 100% full load and C_s = 110 μg/m³ at 50% part load conditions. The calculated outside supply air per person at 100% full load and 50% part load conditions is 15 cfm and 21 cfm, respectively.

Case 2. Conventional VAV System (Class VII in Table 1)

The following data are for the telecommunications zone.
Volume of space = 1133 m³ (40,000 ft³)
Number of people = 300
$\dot{N}$ = 15 μg/min·m³ (based on ASHRAE Standard 62-1981R)
E_v = 0.8 (based on reported test results for air distribution)
V_s = 361 m³/min (12,740 cfm)
E_f = 0.5
F_r = 1.0
C_o = 5 μg/m³

At 50% part-load condition, the system parameters are:

Volume of space = 1133 m³ (40,000 ft³)
Number of people = 210
$\dot{N}$ = 10.5 μg/min·m³ (based on ASHRAE Standard 62-1981R)
E_v = 0.8 (based on reported test results for air distribution)
V_s = 361 m³/min (12,740 cfm)
E_f = 0.5
F_r = 0.5
C_o = 5 μg/m³

To satisfy the condition of $C_s < 50$ μg/m³ and $C_s < 150$ μg/m³ at long and short terms, respectively, and a minimum outside supply air of 15 cfm/person (revised ASHRAE Standard 62-1981R) at part- as well as full-loads, V_o is found to be 6115 cfm with $C_s = 81$ μg/m³ at 100% full load and 3058 cfm with $C_s = 137$ μg/m³ at 50% part-load conditions. The calculated outside supply air per person at 100% full-load and 50% part-load conditions is 20 cfm and 15 cfm, respectively.

Case 3. Modified Water Source Heat Pump (WSHP)/ Packaged Terminal Air Conditioner (PTAC) System (Class VI in Table 1)

This system (Meckler 1988a), which represents a natural extension of the conventional WSHP system for cooling-load-dominated climates, requires less total installed refrigeration capacity and also consumes less energy than a comparable WSHP system (Meckler 1987). Peak electrical demand limiting is obtained through shifting on-peak electrical energy consumption to lower cost, daily off-peak and mid-peak rates available to customers (Meckler 1988b; Meckler and Janssen 1988; Meckler 1988a).

Some indoor contaminants can be eliminated by implementing energy-efficient filtering of return air, thus eliminating the need for excessive amounts of outdoor air. One of the methods of compensating for the effect of reduced ventilation rates within VAV systems involves the introduction of additional filtration and recirculation of ventilation air. This provides enhanced overall filtration to compensate for reduced supply air quantities in response to diminished net space demands for heating and cooling.

In order to compensate for reduced supply air at part-load and the resulting increased contaminant levels, the level of filtration can be increased by placing an additional filter in the bypass duct for the individual WSHP or PTAC and a VAV unit. This additional filter, E-2, is shown in Figure 4.

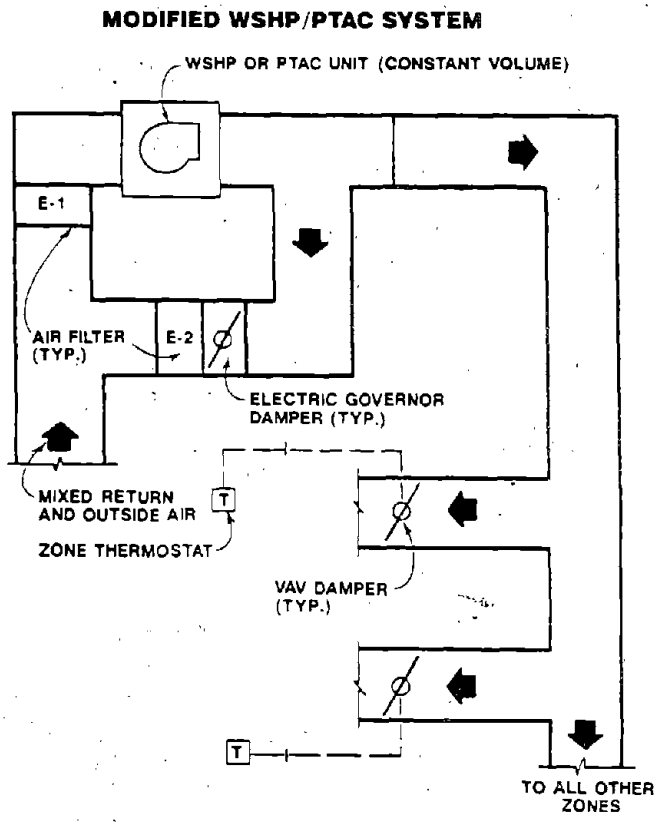

Figure 4 Modified WSHP/PTAC system

Based on several IAQ assessment studies (Meckler 1984, 1985) conducted by our firm, use of such a recycle filtration system can significantly increase the effectiveness of VAV air distribution systems to control indoor air contaminant levels. Installing filters in both the return and bypass positions, as shown in Figure 4, of a unitary WSHP or PTAC unit incorporating a bypass control system for adapting constant-volume air supply unitary units to provide a comparable VAV air distribution system to the conditioned space, also permits cleaner air to be automatically made available at all part-load conditions (Meckler 1988b; Meckler and Janssen 1988).

At 50% part-load condition, the system parameters for the telecommunications zone are:

Volume of space = 1133 m³ (40,000 ft³)
Number of people = 210
$\dot{N}$ = 10.5 μg/min.m³ (based on ASHRAE Standard 62-1981R)
E_v = 0.8 (based on reported test results for air distribution)
V_s = 361 m³/min (12,740 cfm)
E_f = 0.67
F_r = 0.5
C_o = 5 μg/m³

The combined filter effectiveness, E_f, above for parallel connection is calculated using:

$$E_f = 1 - \frac{(1 - E_1)}{1 + X[1 + (1 - E_1)(1 - E_2)]} \qquad (1)$$

where X is the bypass percentage (Meckler and Janssen 1988) and $E_1 = 0.5$ and $E_2 = 0.9$.

To satisfy the condition of $C_s < 50$ μg/m³ and $C_s < 150$ μg/m³ at long and short terms, respectively, and a minimum outside supply air of 15 cfm/person (revised ASHRAE Standard 62-1981R) at part- as well as full-loads, V_o is found to be 3185 cfm with $C_s = 125$ μg/m³. The calculated outside supply air per person at 50% part-load condition is 15 cfm. The required V_o of 3185 cfm for this system is less than that required (4358 cfm) for a conventional VAV system.

Case 4. Integrated Desiccant Cold Air Distribution (IDCAD) System (Class VI in Table 1)

The IDCAD system (Meckler 1981, 1988c) consists of an evaporative chilling (EC) module and a desiccant dehumidifier (DD) module integrated into a multi-duct air-handling (MDAH) module, as shown in Figure 5. Each fully integrated dual-duct/VAV desiccant air-handling unit serves a combination of interior and exterior conditioned spaces by means of a unique three-deck air distribution system that takes full advantage of VAV energy-saving benefits for space cooling while maintaining satisfactory ventilation efficiency at varying part-load conditions by different means in the building's interior and exterior zones, as will be discussed.

Referring to Figure 5, notice that this system uses three supply fans, one for the hot deck and two for each cold deck (operating at 40°F supply air temperature), thereby allowing for separation of exterior and interior zones while reducing return air ductwork and separately monitoring for IAQ. Each supply fan's volume is controlled independently by the static pressure in its respective duct. Common return fan airflow is controlled relative to the sum of the hot and cold fan volumes using flow-measuring stations (FMS) to ensure positive tracking.

TABLE 4

Performance Summary of Four Different VAV Systems at 100% Full- and 50% Part-Load Conditions for Various Zones Using IAQ Procedure

Zone	Ventilation Rate Procedure CFM/Person	Indoor Air Quality Procedure CFM/Person (C_s, μg/m³) VAV System with Constant OSA 100% Load	VAV System with Constant OSA 50% Load	VAV System w/Proportional OSA 100% Load	VAV System w/Proportional OSA 50% Load	Modified WSHP/PTAC 100% Load	Modified WSHP/PTAC 50% Load	IDCAD 100% Load	IDCAD 50% Load
Telecommunications	20	15 (89)	21 (110)	20 (81)	15 (137)	15 (89)	15 (125)	15 (129)	19 (130)
Conference Rooms	20	15 (93)	21 (109)	21 (84)	15 (137)	15 (93)	15 (129)	15 (133)	17 (140)
Offices	20	15 (65)	22 (135)	23 (63)	16 (147)	15 (65)	15 (121)	15 (107)	24 (94)
Shops	15	15 (78)	22 (114)	28 (74)	20 (140)	15 (78)	13 (124)	15 (118)	24 (110)

Each supply fan is sized for the anticipated maximum coincident hot or cold volume, not the sum of its instantaneous peaks. Each cold deck can be maintained at a constant temperature either by operating a cooling coil as a wet economizer with only a minimum of outdoor air (in lieu of a more costly free cooling air economizer) when outside air is below the cold deck setpoint. Cold air volumes and the refrigeration capacity are determined by the sum of the simultaneous peaks of the cold air requirements for all (i.e., interior and exterior) zones.

Also notice that the return air fan is sized only for returning exterior zone space air since interior zones can use close-coupled, fan-powered VAV mixing boxes, representing major savings in operating cost, initial cost, and usable building space. Use of combination dual-duct VAV mixing boxes equipped with suitable terminal air cleaners permits higher recirculation rates and lower outdoor air ventilation rates without sacrificing IAQ.

At 100% full-load condition, the IDCAD system parameters for offices zone occupancy are:

Volume of space = 2039 m³ (72,000 ft³)
Interior = 6000 ft²
Exterior = 3000 ft²
Number of people = 63
$\dot{N}$ = 5 μg/min·m³ (based on ASHRAE Standard 61-1981R)
E_v = 0.8 (based on reported test results for air distribution)

INTEGRATED DESICCANT COLD AIR DISTRIBUTION (IDCAD) SYSTEM

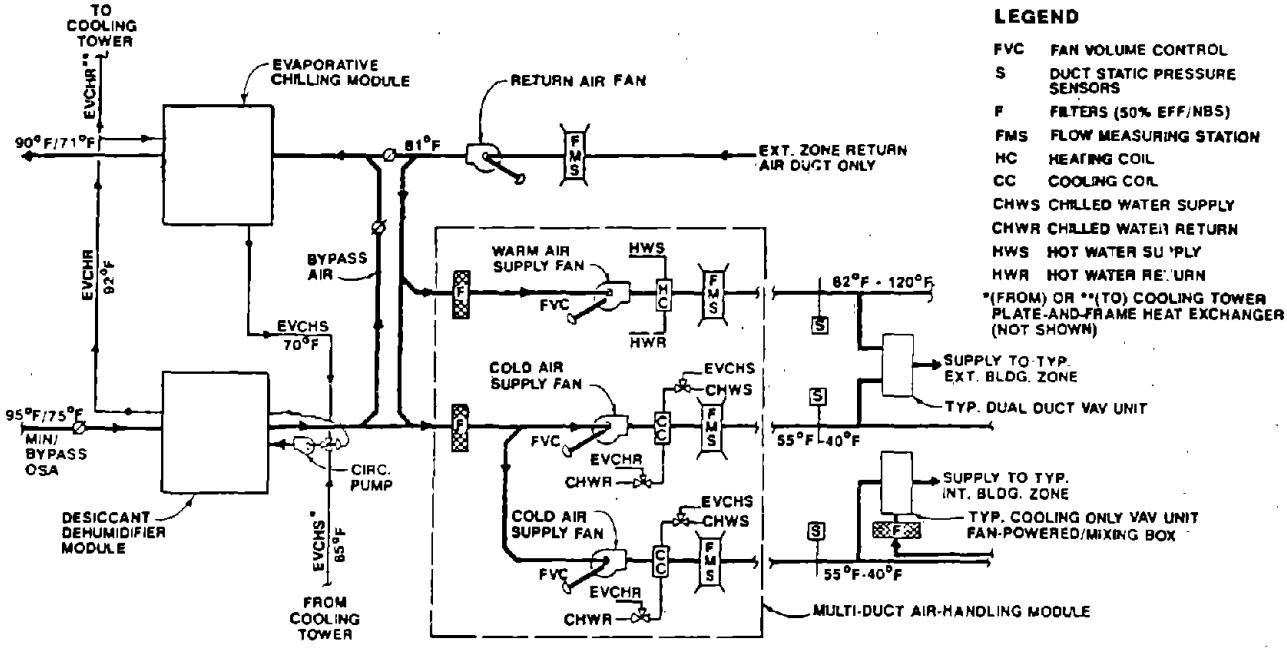

Figure 5 Integrated desiccant cold air distribution (IDCAD) system

V_s = 210 m³/min (7430 cfm)
E_f = 0.5
F_r = 1.0
C_o = 1.0 μg/m³

To satisfy the condition of C_s < 50 μg/m³ and C_s < 150 μg/m³ at long and short terms, respectively, and a minimum outside air of 15 cfm/person (revised ASHRAE Standard 62-1981R) at part- as well as full loads, V_o is found to be 975 cfm with C_s = 107 μg/m³. The calculated outside air per person is 15 cfm.

At 50% part-load condition (70% part-load for interior and 30% part-load for exterior zones), the system parameters for the interior offices zone are:

Volume of space = 1359 m³ (48,000 ft³)
Number of people = 29
$\dot{N}$ = 3.5 μg/min·m³ (based on ASHRAE Standard 61-1981R)
E_v = 0.8 (based on reported test results for air distribution)
V_s = 105.2 m³/min (3715 cfm)
E_f = 0.5
F_r = 1.0
C_o = 1.0 μg/m³

The system parameters for the exterior offices zone are:

Volume of space = 680 m³ (24,000 ft³)
Number of people = 11
$\dot{N}$ = 2.5 μg/min·m³ (based on ASHRAE Standard 61-1981R)
E_v = 0.8 (based on reported test results for air distribution)
V_s = 105.2 m³/min (3715 cfm)
E_f = 0.5
F_r = 0.7
C_o = 1.0 μg/m³

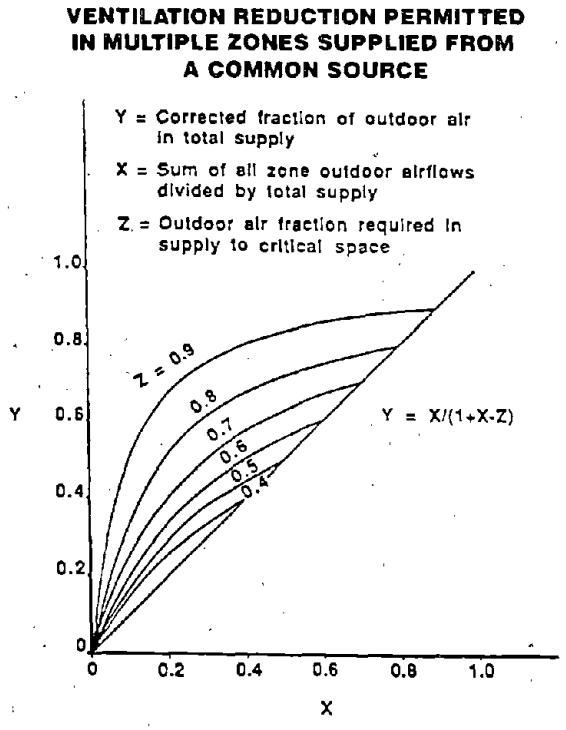

Figure 6 Ventilation reduction permitted in multiple zones supplied from a common source

To satisfy the condition of C_s < 50 μg/m³ and C_s < 150 μg/m³ at long and short terms, respectively, and a minimum outside air of 15 cfm/person (revised ASHRAE Standard 62-1981R) at part- as well as full loads, V_o is found to be 682 cfm with C_s = 102 μg/m³ for interior zone, and 292 cfm with C_s = 78 μg/m³ for the exterior zone. The calculated outside air per person is 23 cfm and 28 cfm, respectively. Notice that

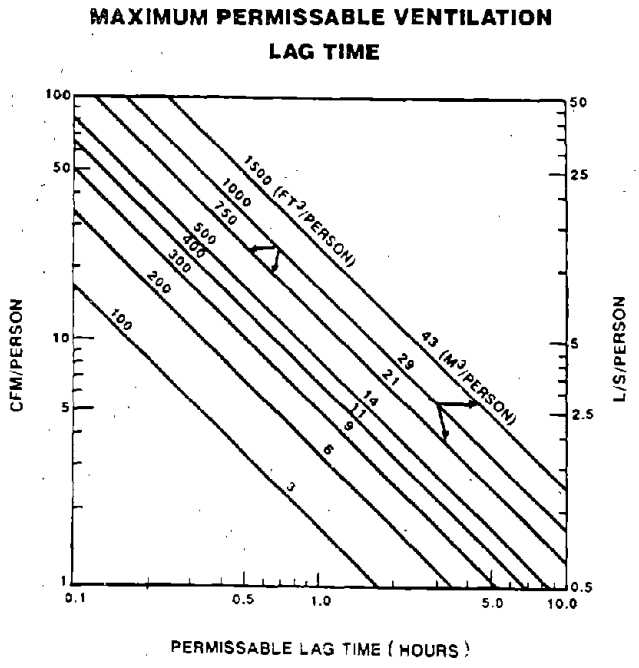

Figure 7 Maximum permissible ventilation lag time

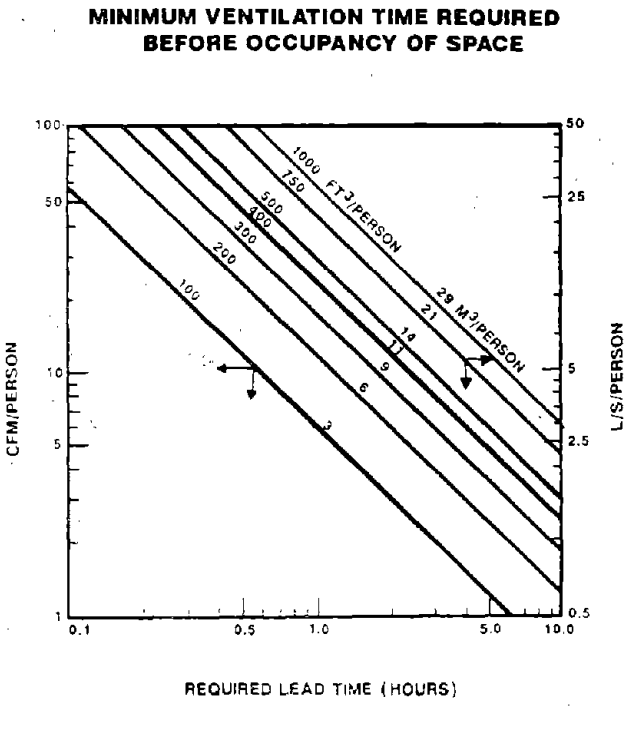

Figure 8 Minimum ventilation time required before occupancy of space

C_o (in both part- and full loads) is decreased to 1.0 since the DD module in Figure 5 utilizes a spray coil liquid desiccant dehumidifier to clean the outdoor air, thereby reducing C_o from its initial 5.0 value to 1.0. This system eliminates the need to provide outside air at full-load to satisfy part-load conditions of C_s levels seen in other systems.

Table 4 summarizes the results of the four above-referenced illustrated case studies listing the required outside supply air per person (cfm) and indoor contaminant level, C_s, as determined by the use of IAQ procedure. This contrasted with VRP for each of the four VAV systems. Referring to Table 4, notice that if one simply relies on the VRP for, say, shops occupancy and employs the conventional VAV system in Case 2, it is likely that the NPAAQS studied (i.e., 150 μg/m³) for the short-term would be exceeded, contrary to the intent of ASHRAE Standard 62-1981R (i.e., with respect to NPAAQS being exceeded indoors). Using the IAQ procedure as a means to validate the VRP results may be advisable to confirm compliance with the NPAAQS criteria. The parameters are calculated the same way as above at 100% full-load and 50% part-load conditions.

If ventilation reduction in multiple zones supplied from a common source is required, it can be calculated using the graph in Figure 6 (ASHRAE 1988). For example, for the combination of communications and offices zones in a VAV system with constant temperature and proportional outdoor air (Class VII in Table 1), the ventilation reduction is calculated as follows:

$$X = \frac{4378 + 975}{12{,}740 + 13{,}000} = 0.21 \qquad (2)$$

$$Z = \frac{4358}{12{,}740} = 0.34 \qquad (3)$$

where X is the sum of all zone outdoor airflows divided by total supply, and Z is the outdoor air fraction required in supply to critical space. From the graph in Figure 6, the corresponding ventilation fraction (Y) is 0.24, which implies that the total outside air is 25,740 x 0.24 = 6180 cfm.

LEAD/LAG PROCEDURE

To provide adequate dilution of air to maintain the contaminant level within acceptable levels of a ventilation system with variable occupancy, outdoor air quantity must be adjusted either by dampers or stopping and restarting ventilation (ASHRAE 1988). This adjustment may lag or should lead occupancy, depending on the contamination source and the change in occupancy. When the contamination level is due to occupancy only, it is dissipated during unoccupied periods and supply of outdoor air may lag occupancy. If the contaminant level in a zone is independent of occupancy, outdoor air supplied must lead occupancy to have acceptable levels at the start of occupancy. Figures 7 and 8 illustrate the lag and lead times, respectively, necessary to obtain acceptable levels for variable occupancy.

The following two examples are provided to illustrate lag and lead time for the telecommunications and conference rooms zones. For the conference rooms zone, the contaminant level is assumed to be due to occupancy, and the contaminant level for the telecommunications zone is assumed to be independent of occupancy due to equipment-related contamination.

For the 32,000 ft³ conference rooms zone and calculated outside supply air of 15 cfm/person in Case 1, the air capacity in the space is 160 ft³/person. Then, from the graph in Figure 7 (ASHRAE 1988), the corresponding lag time is 0.15 hour or 9 minutes. This means that the system must be operated an extra 9 minutes.

By the use of the same procedure as above, for the 40,000 ft³ telecommunications zone and calculated outside supply air of 15 cfm/person, also in Case 1, the air capacity in the space is 133 ft³/person. Then, from the graph in Figure 8 (ASHRAE 1988), the corresponding lead time is 0.6 hour or 36 minutes. This implies that outdoor air supplied leads occupancy to have acceptable levels at the start of occupancy.

SUMMARY

Since a large amount of our time is spent indoors, IAQ is a very important factor to our health and comfort. As pointed out above and by others (Meckler and Janssen 1988; Morey 1988), IAQ control directly affects the energy consumption of a building due to HVAC system ventilation air requirements and air distribution characteristics. For example, conditioning and distribution costs associated with moving air in buildings account for 50% to 60% of the nation's total building energy consumption, estimated at more than $80 billion per year. If building ventilation is improved, not only could occupants have better IAQ, but building owners could also save up to $2 billion a year (SERI 1988).

The above-reported case studies examined four different VAV system options for a representative office building located in metropolitan Los Angeles and an SCAQM district. Applying the latest SCAQM district data, it would appear that the following outdoor air pollutants, particulates (PM 10), carbon monoxide, and ozone levels have consistently exceeded the limits with respect to existing state and federal standards set by the SCAQMD within the last six months. Where such information exists (e.g., in the case of shops occupancy at 50% part-load [refer to Table 4 for Case 2 tabulation]), optional use of the VRP would result in excess of C_s of 150 μg/m³ for short-term occupancy, as pointed out earlier. As more information becomes available, indiscriminate use of VRP may have to be re-examined. Accordingly, the newly proposed IAQ procedure can be utilized to verify the adequacy of the VRP values as well as to more directly compute levels of indoor air contaminants within our occupied building space applying the techniques of IAQ zoning described above.

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DISCUSSION

Hal Levin, Hal Levin & Associates, Santa Cruz, CA: If you use the ventilation rate procedure in an area where CO levels exceed NAAQS limits, ASHRAE Standard 62-1981R permits a reduction in outdoor air levels. Do you interpret the standard to require filtration of recirculated air and application of the air quality procedure when outdoor air supply is reduced to control carbon monoxide because no practical air cleaning is available for CO?

M. Meckler, Meckler Engineers Group, Encino, CA: The question you have raised presents a similar situation to that which I have tried to illustrate under those circumstances where outdoor particulate levels exceed published NAAQS levels for long- and short-term exposures (see Table 2).

Although the proposed ASHRAE Standard 62-1981R does not specifically set up a "decision tree" approach to bypassing use of the optional Ventilation Rate Procedure, I believe it is incumbent upon HVAC designers to recognize that only through use of the alternate Indoor Air Quality Procedure can one estimate appropriate space concentrating levels for any OSA contaminant known to exceed published NAAQS levels.

In an earlier paper prepared for IAQ '88 (see References—Meckler, M., and Janssen, J. 1988), John Janssen and I outlined a design approach employing treatment of recirculated air in lieu of indiscriminate use of excessive amounts of dilution OSA as a potentially more cost-effective design strategy. As you have pointed out, removal of carbon monoxide from air (i.e., although difficult at present) may still be necessary, particularly if automatic reduction of OSA supply would result in less than 15 cfm per person (or a higher than 1000 ppm carbon dioxide space concentration level).

Under these circumstances, it may be preferable to attempt to characterize carbon monoxide levels (at the specific site and elevation, etc.) likely to be entering the OSA intake. For example, if high levels of automobile traffic are anticipated on adjacent streets (or if the building is located in the vicinity of a freeway, etc.), then introducing outdoor air from street level should be avoided.

William A. Turner, Harriman Associates, Auburn, ME: Where did the N values used in the examples come from? Are they conservative, and did you assume a certain amount of tobacco smoke and other sources?

Meckler: The N values listed were backed out of actual test data (i.e., noted under text references as Meckler 1985), as well as other available published data by other investigators of office occupancies. While approximate, they are believed to be generally representative for particulates in the listed occupancies. Since our test data were obtained under normal occupancy conditions, representative amounts of ETS and other sources are included.

Carl N. Lawson, LRW Engineers, Tampa, FL: Did you consider the use of VAV for outside air and, if so, was the outside air filtered? Was any consideration given to laser printers and photo copiers?

Meckler: With respect to outside air (OSA) two scenarios were considered, namely one involving proportional (i.e., Case IV in Table 1) and the other constant OSA delivery rate (Case III in Table 1) at various space part-load conditions, as illustrated in Table 4. Referring to Table 4, it can be seen that significantly higher levels of Cs result particularly at 50% part-load. Provision for maintaining a constant OSA delivery rate to conditioned spaces at all part-load conditions will generally require use of a separate OSA fan. Use of automatic balancing dampers is often problematic. For the various metropolitan Los Angeles occupancy scenarios listed, it was assumed that some filtration of outside air would be necessary down to a level of 5 g/m^3 in order to maintain the (generally acceptable) values of Cs listed.

Although no specific consideration was given to laser printers, etc., particulate generation rates (N) for some indicated occupancies would have included use of photocopiers, where appropriate.

PERCEIVED AIR QUALITY AND THE THERMAL ENVIRONMENT

L.G. Berglund **W.S. Cain**

ABSTRACT

Occupants' perceptions of air freshness, stuffiness, and acceptability are predictably influenced by the thermal parameters of the environment. This conclusion was derived from the subjective responses of 20 subjects studied at three temperatures, three humidities, and three activity or metabolic rates. Air was perceived to be fresher and less stuffy with decreasing temperature and humidity. The effect of temperature was linear and stronger than humidity. The effect of humidity on freshness, stuffiness, and acceptability of air quality was smaller in the dew point range of 35° to 52°F (2° to 11°C) than in the range from 52° to 68°F (11° to 20°C). Air quality was typically judged not very acceptable when relative humidity exceeded 50%. The perception of the freshness, staleness, and stuffiness proved independent of metabolic rate in the activity range from sitting quietly to continuous walking. However, the acceptability of the air decreased when the subjects felt warmer than neutral and when their skin felt damp or wetter, both of which are affected by metabolic activity.

INTRODUCTION

The perceived quality of the air in a building depends upon a combination of the chemical and physical properties of the air. For the person fresh from another space, chemical properties will predominate. Specifically, the person's judgment of acceptability will correlate strongly with level of odor (Cain et al. 1983). A place with a high level of occupancy odor, for example, will be judged unacceptable, even though the visitor to the space may not consciously focus on odor (Cain 1979). The air quality may just seem poor.

For the person who has occupied a space for a while, the chemical properties of the atmosphere will generally seem less salient than its physical properties. That is, odor will have less relevance than temperature, humidity, and air motion. Higher than desirable temperatures, high humidity, and low air motion may create unacceptable feelings of stuffiness and closeness. The introduction of fresh, outside air may alleviate such feelings insofar as it reduces temperature and humidity. On the other hand, cooler and drier air may suffice even without introduction of fresh air. Hence, the need for fresh air can rest largely on the illusion that cooler and drier air is somehow freer of contaminants.

Recent investigations of ventilation requirements for human comfort have focused more on the chemical parameters of the atmosphere (e.g., occupancy odor, environmental tobacco smoke, formaldehyde) than on physical parameters and, accordingly, more on the judgments of visitors fresh from another space than occupants of the space. In actual field circumstances, however, judgments of poor air quality will most often arise from occupants.

The present investigation examines the perception of air quality for various combinations of physical parameters. It addresses such issues as the relative importance of temperature vs. humidity on perceived air freshness. In its focus on the occupant, it has something in common with the classic investigation of the New York State Commission on Ventilation, 1913–1922 (Winslow 1922). The present results, as well as those of that earlier study, suggest the need to understand the combined effect of both physical and chemical factors on perceived air quality. The results reported here formed part of a larger investigation (Berglund 1989) on human responses to temperatures and humidities of air-conditioned environments in the summer.

EXPERIMENTAL PROGRAM

The experiments were conducted in a 17.5 ft by 20.5 ft by 8 ft chamber (Kjerulf-Jensen et al. 1975) that provides uniform conditions of temperature and humidity with an air speed of 10 fpm (0.05 m/s). Human responses were obtained at conditions that bracketed the ASHRAE summer comfort zone. Specifically, test temperatures equaled 70°, 75°, and 81°F (20°, 24°, and 27°C) (air temperature = mean radiant temperature) with humidity levels defined by dew point temperatures of 36°, 52°, and 68°F (2°, 11°, and 20°C). Humidification was achieved by injection of low-pressure steam made from untreated tap water. The ventilation rate of the chamber, measured via decay of CO_2 under actual test conditions, averaged 157 ± 18 cfm, with no significant variation with temperature or humidity.

Twenty test subjects (10 men and 10 women) with diverse socio-economic status participated. Ages of the subjects ranged from 18 to 62 with an average of 35 years.

Occupants of commercial spaces, such as offices and stores, typically exist at various levels of activity from sitting quietly to continuous walking. Increased activity results in increased physiological effort, metabolic heat, and perspiration, all of which may affect sensations of comfort and air quality. The study accordingly assessed perceptions and physiological responses at three activity states from sedentary (1 met) to continuous walking (3 met), where 1 met = 58.3 W/m², the nominal energy level of a resting person. The intermediate level (2 met) was accomplished through a repetitive routine of 5 min walking and 5 min standing.

Each of the 20 subjects participated in 27 different hour-long test conditions defined by the combination of the three temperatures, three humidities, and three metabolic rates. Such a design offered considerable sensitivity to small differences in responses.

The subjects wore their own summer clothing (slacks, long- or short-sleeve shirts). The insulation level of their attire was evaluated each day using the checklist method (ASHRAE 1981). It averaged 0.56 ± .04 clo. For reference, a winter business suit has a value of about 1 clo.

Twenty-five percent of the subjects (five) were instrumented to measure internal and skin temperatures, heart rate, and skin wettedness. The temperatures were measured

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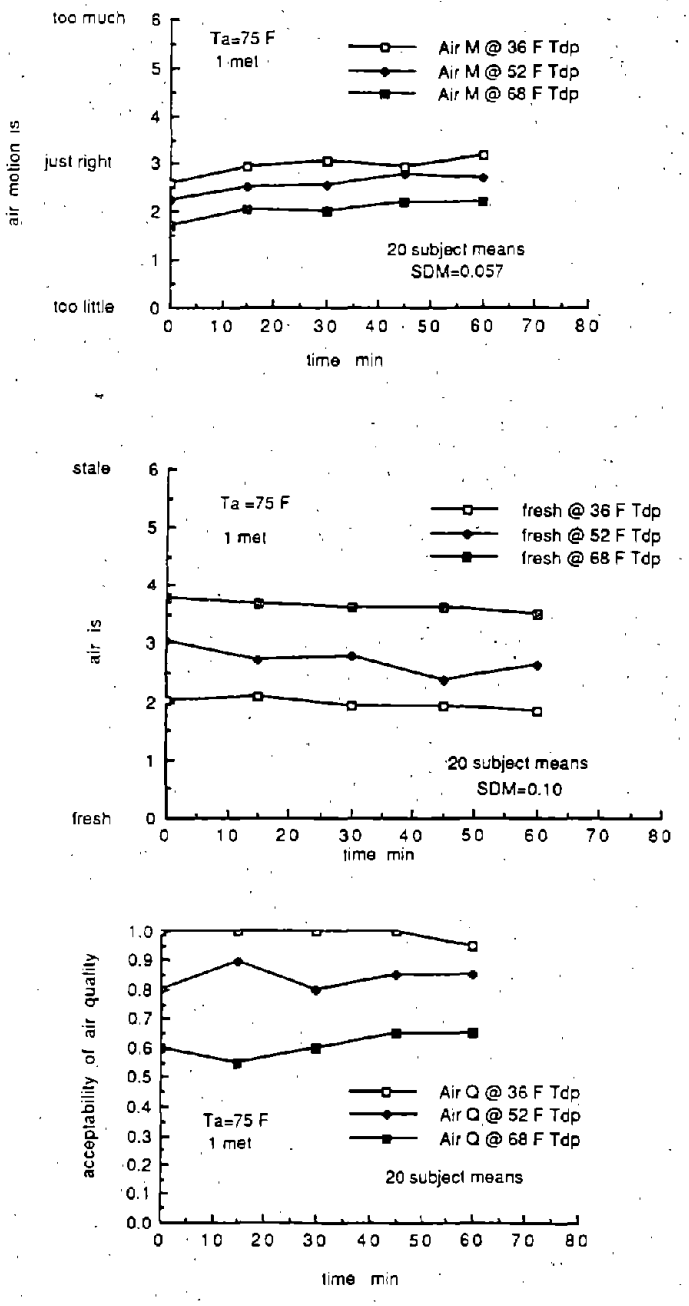

Figure 1 Perceived air motion, freshness, and acceptability over time

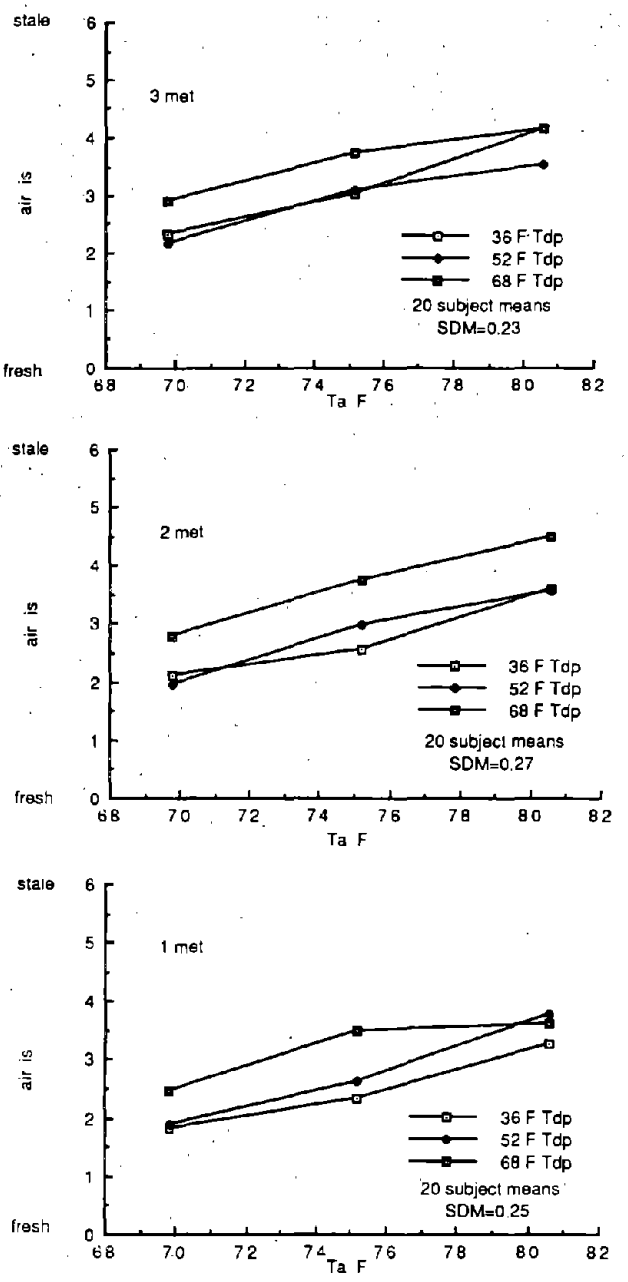

Figure 2 Perception of air's freshness at 1, 2, and 3 met

via thermocouples read by an on-line computer. Internal temperature was measured in the esophagus at the level of the heart. Skin temperatures were measured on the face, hand, upper and lower arm, chest, back, thigh, and calf. Skin wettedness was calculated from humidity measurements made under the clothing. Miniature dew point sensors on the back, chest, arm, thigh, and calf measured humidity 2 mm above the skin. Local dew point and skin temperatures, together with the ambient humidity, were combined to determine the local skin wettedness (w)—defined as the ratio of local evaporation rate (E) to the maximum evaporation rate ($Emax$) that would occur when the skin at that point is completely covered with water. Maximum evaporation occurs when the measured vapor pressure (Pm) just above the skin equals the saturation vapor pressure ($Pssk$) for water at skin temperature. At submaximal evaporation rates the skin is not completely covered with water and the measured dew point temperature is less than the temperature of the skin. Assuming the mass transfer characteristics through the clothing and boundary layers are the same for maximal and submaximal evaporation, skin wettedness by definition ($w = E/Emax$) becomes the ratio of the vapor pressure differences for the two cases:

$$w = (Pm - Pa)/(Pssk - Pa),$$

where Pa represents ambient vapor pressure. The mean skin wettedness under clothing and the mean skin temperature comprise the area-weighted averages of the local values.

The subjects were usually tested in groups of five except for the instrumented subjects, who were tested individually on a treadmill. The others could either walk about the test chamber or use the treadmill for the walking. Tests lasted one hour for the uninstrumented subjects and a bit longer for the instrumented subjects.

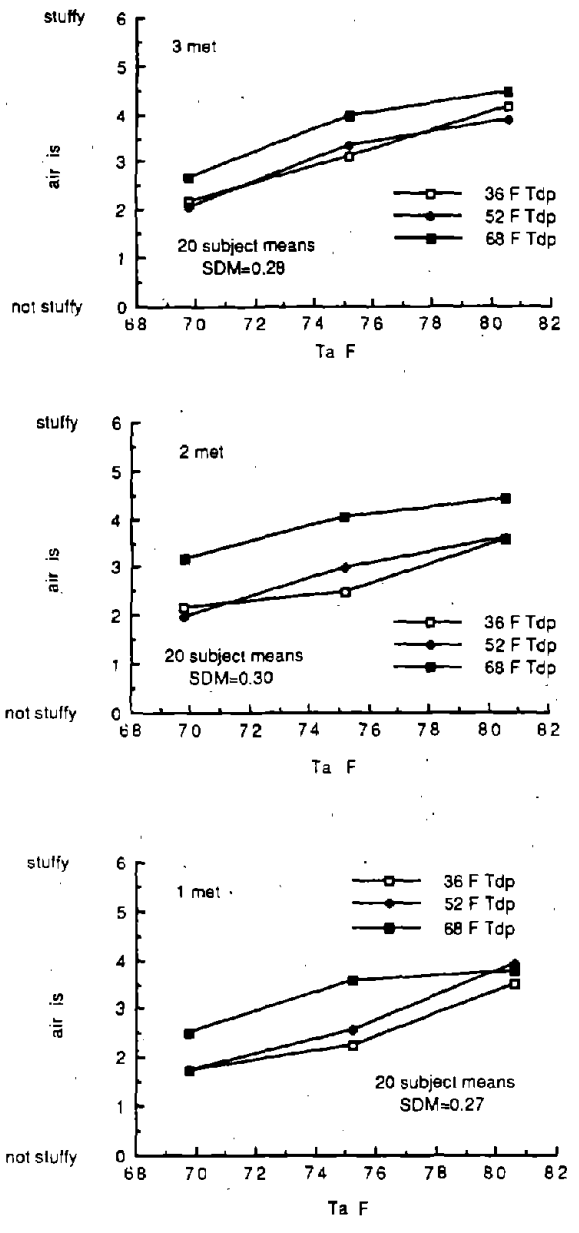

Figure 3 Stuffiness of the air as judged by 20 subjects at three levels of activity

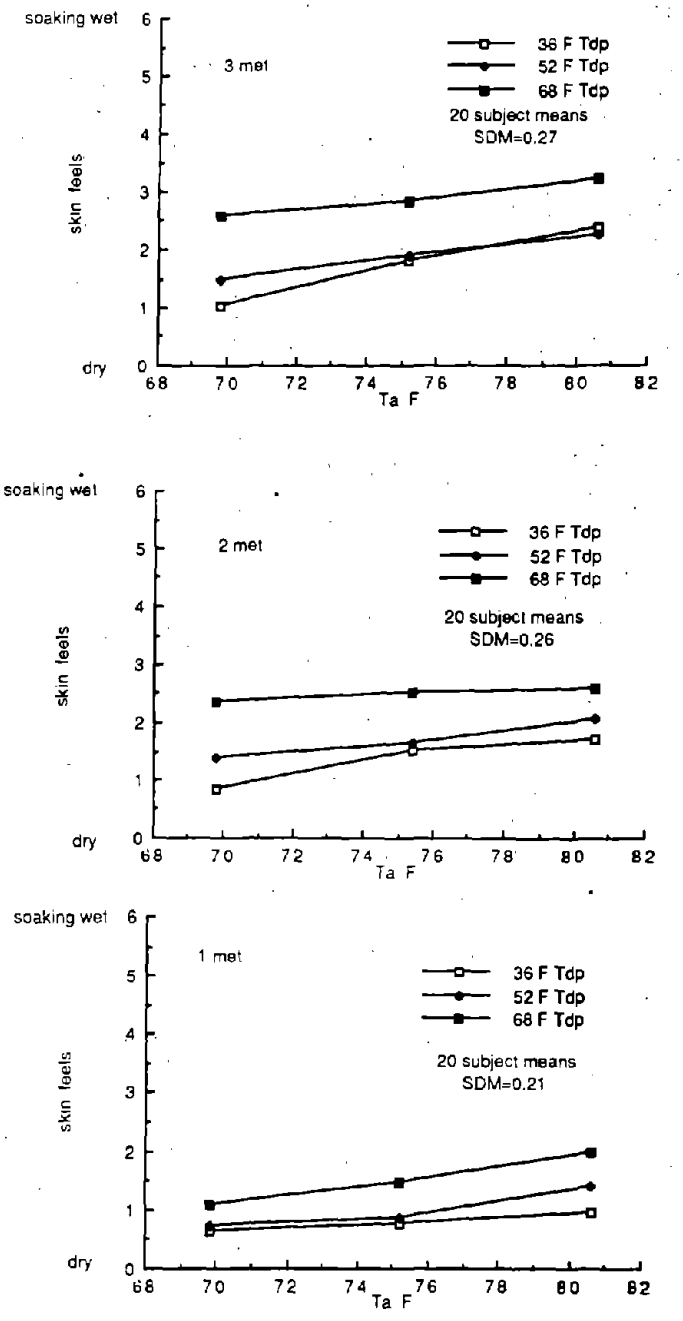

Figure 4 Perceived skin wettedness at three levels of activity

Instrumented subjects had their rate of oxygen consumption measured twice per test with the open-loop method. The overall average metabolic rates for the activities calculated from these measurements were:

Sitting	0.94 met
Intermittent walking	1.95 met
Continuous walking	2.82 met

Energy production during intermittent walking equaled about twice that of sitting and the heat produced by continuous walking equaled about three times that of sitting. All of the metabolic energy of these experiments ended up as heat since the subjects did no net thermodynamically useful work.

Participants gave subjective responses immediately upon entering the chamber and every 15 min thereafter using a questionnaire. Three of the questions concerned air quality directly (freshness, stuffiness, and acceptability), whereas four concerned air quality only indirectly (skin moisture, humidity, air motion, and thermal sensation). The subjects marked a line to indicate how they felt at that moment. For the air freshness scale, the line was bounded by "fresh" at one end and "stale" at the other. For stuffiness, the line was bounded by "stuffy" and "not stuffy"; for humidity, by "very dry" and "very humid"; for skin wettedness or skin moisture, by "dry" and "soaking wet"; and for air motion, by "too much" and "too little." The thermal sensation scale comprised the nine-point ASHRAE scale from "very cold" to "very hot." For the question of acceptability, the subjects judged whether or not the air quality was acceptable, under instructions that an unacceptable condition would evoke a behavioral action to improve the climate and/or reduce discomfort, e.g., open a window, turn on a fan, change the thermostat setting, complain, or leave.

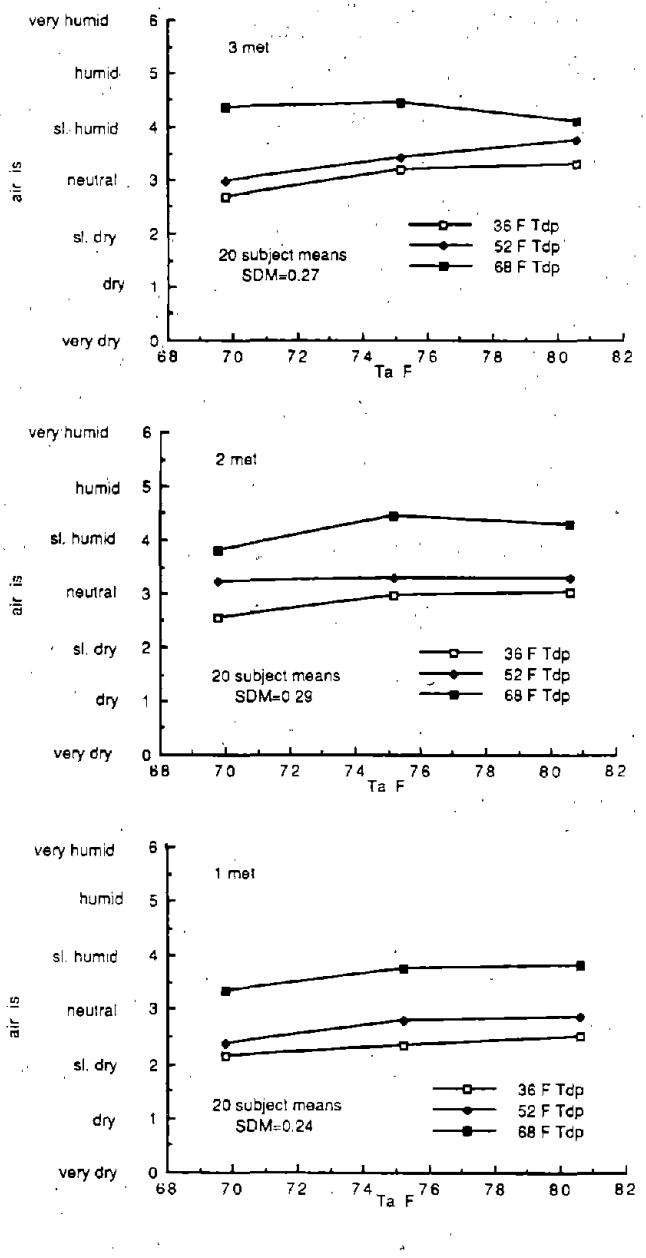

Figure 5 Perceived humidity level of ambient environment at three activity levels

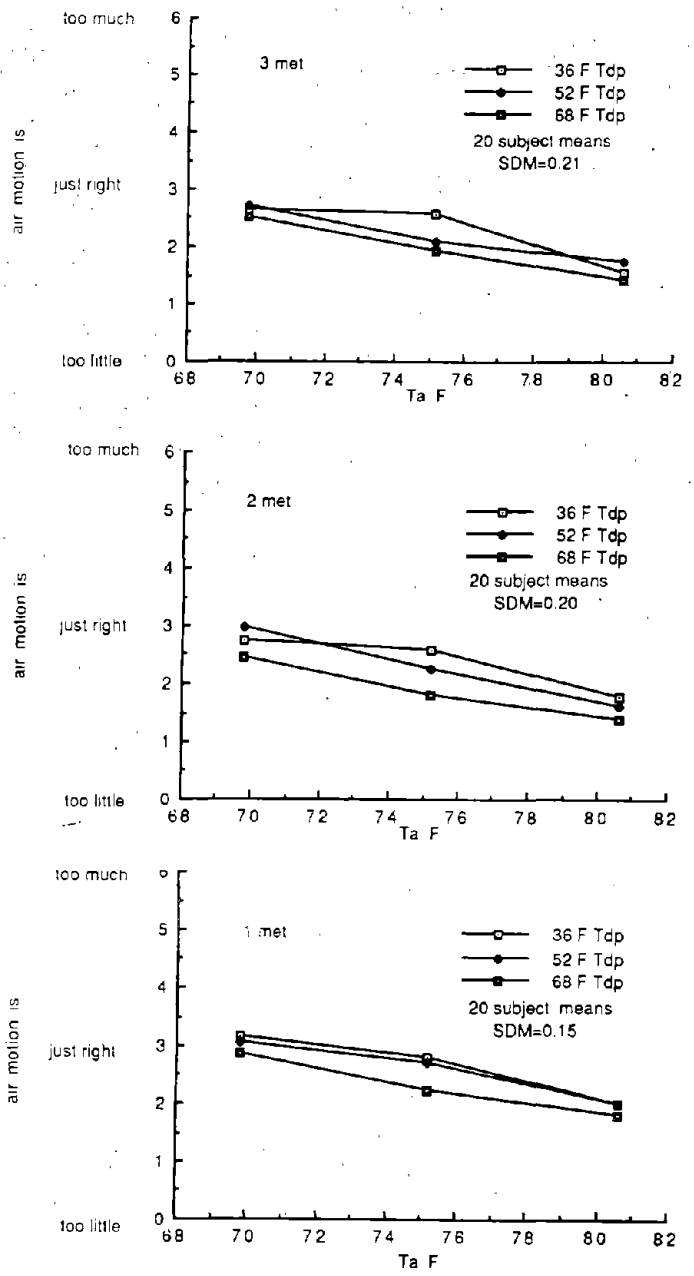

Figure 6 Adequacy of the air motion at three levels of activity

RESULTS

Responses Over Time

Figure 1 depicts the perception of air motion, freshness, and acceptability over time for the sedentary case at 75°F. Perceived air motion increased slightly over time at all three dew points. At all points in time, however, air motion appeared slower at the higher humidities. Perceived air freshness and acceptability proved even more stable with time. Higher humidity, however, made the air appear less fresh and less acceptable. A slightly greater time dependence arose with thermal sensation and perceived skin wettedness, both of which reached fairly stable levels by 45 min. The physiological measurements of internal and skin temperature and skin moisture reached steady levels within 30 min. In Figure 1 and those that follow, the data points indicated are the means of 20 subjects. The average standard deviation of the means (SDM) is also indicated where applicable.

Steady-State Responses

Since the data changed little with time, particularly after 30 min, we will focus hereafter on steady-state values. The figures that follow contain responses given at the end of the testing and figures are arranged to show a given response at all three activity levels.

The subjects perceived the air as less fresh, i.e., more stale, at higher temperatures and dew points (Figure 2). The effect of temperature was more pronounced than that of humidity. The responses were, however, less consistently related to activity.

Stuffiness (Figure 3) was rated similarly to freshness-staleness, i.e., stuffiness increased with increasing temperature and humidity. Activity had only a slight effect on the perception. The correlation between perceived freshness-staleness and stuffiness equaled 0.98. For all practical purposes, the judgment of one attribute seems interchangeable with that of the other.

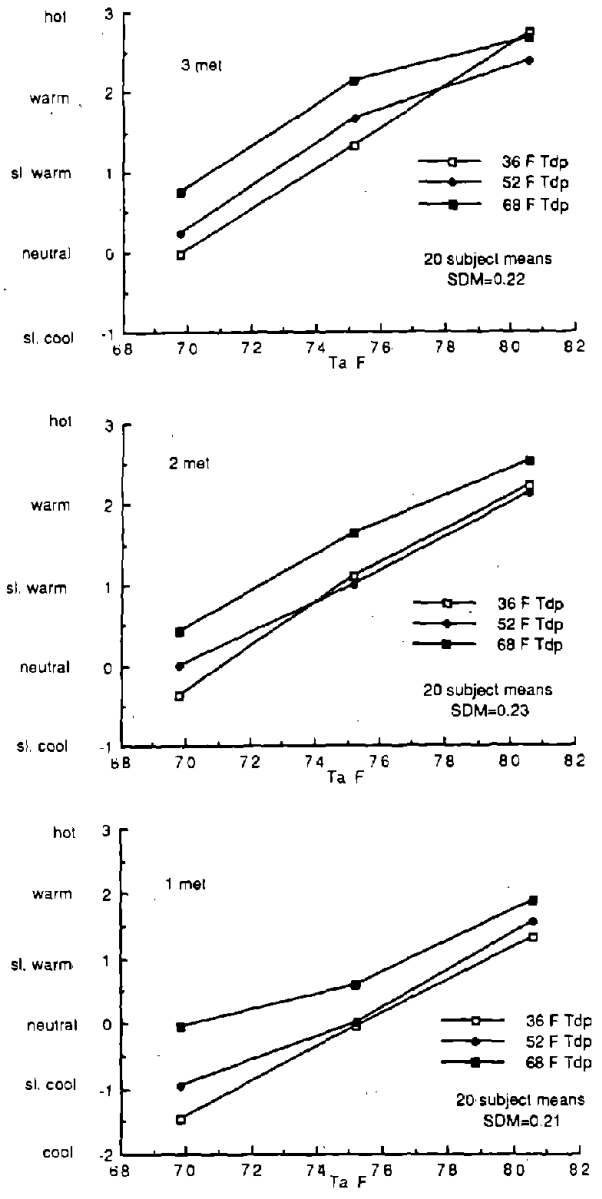

Figure 7 Thermal sensations after one hour at three activity levels

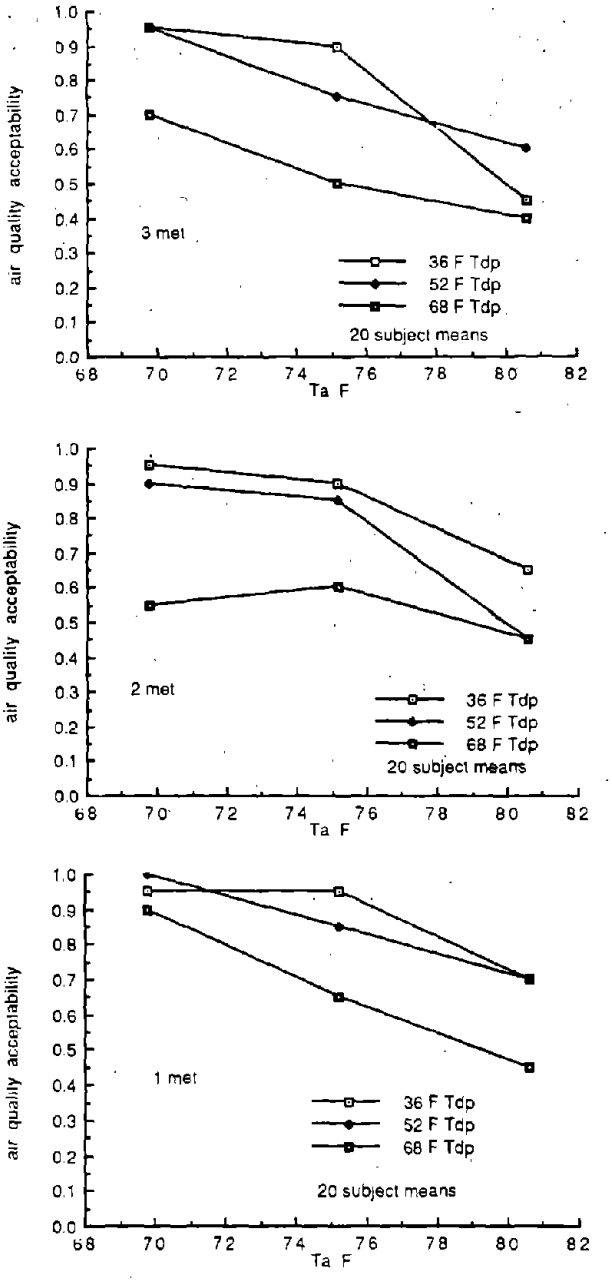

Figure 8 Acceptance of air quality at 1, 2, and 3 met

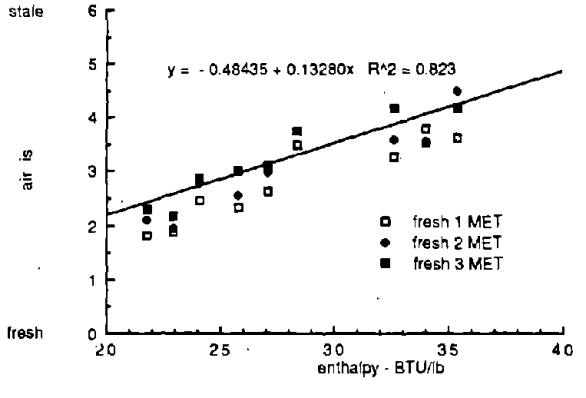

Figure 9 Perceived freshness related to the enthalpy of the environment

The skin felt wetter with increasing temperature, humidity, and activity (Figure 4). This perception of skin moisture may have affected acceptability and freshness perceptions, though by what means is uncertain. The correlation of perceived to measured skin moisture equated 0.92.

Judgments about the humidity were consistent with actual conditions, though compressed in comparison to the range of humidities explored (Figure 5). Ambient temperature had a minor influence on humidity assessments. Activity level had a greater influence, probably because of increased perspiration and wettedness at higher activity levels. Subjects judged the air more humid with increased activity.

The constant 10 fpm (0.05 m/s) air motion of the test room was judged to be less adequate with increasing temperature, humidity, and activity (Figure 6). The effect was more pronounced for temperature than for humidity and activity, though still relatively minor.

Mean steady-state thermal sensations for the three levels of activity appear in Figure 7. At a given temperature, subjects felt warmer at the higher activity levels. The response to temperature was quite linear and the response to humidity was uniform among the activities. Decreasing the humidity at a given temperature caused the subjects to feel cooler. However, the perceived difference between the 52° and 36°F dew point conditions was small.

The question of the acceptability of air quality may be the most important from a design or operator's point of view. It was strongly affected by humidity, as shown in Figure 8. The 68°F dew point condition (RH > 65%) was particularly associated with unacceptable air quality judgments. Recall that the subjects could answer the acceptability question only with yes or no. They were instructed that an unacceptable environment is one that would evoke a behavioral action to improve the situation.

DISCUSSION

The subjective responses of the participants in the present study changed very little over time. For most attributes, the initial and final responses were the same or nearly so, particularly for those sensations related to air quality. The participants immediately perceived the air as less stale, less stuffy, and more acceptable at drier and cooler conditions. The immediateness of their impressions, though somewhat obscure in origin, is intriguing.

The environmental chamber had little background odor and, therefore, any such odor seems an unlikely source of the initial impression of staleness/stuffiness. The chamber contained essentially no active odor sources, except for the occupants themselves, and had the relatively high ventilation rate of at least 30 cfm occupant. Such a ventilation rate would typically prevent more than a trivial buildup of odors over time and would, in any case, allow for fresh starting conditions. It seems more likely that the occupants decided upon relative staleness/stuffiness on the basis of immediate impressions of temperature and humidity. Whether persons with less experience than those studied here would show such keen discrimination remains to be seen.

Air temperature had a somewhat more potent influence on perceived air quality than did humidity. On average, a 1°F change in air temperature had the same effect on staleness as a 6°F change in dew point temperature. The ability of the present subjects to assess humidity reliably nevertheless holds interest. They proved as consistent when sedentary as when active and as consistent at the lowest as at the highest temperature. For both perceived humidity and perceived staleness/stuffiness, the increase in dew point from 52°F to 68°F proved more salient than the increase from 36°F to 52°F.

Staleness (S) can be related to air temperature (T), dew point (DP), and metabolism (M) by the regression equation:

$$S = 0.141\ T + 0.0211\ DP + 0.2095\ M - 9.066$$
$$(r^2 = 0.95)$$

where T and DP are in °F, M is in mets, and S is a 0–6 scale with 6 representing "stale" and 0 "fresh." Staleness can also be related to temperature and humidity, as in Figure 9, where the thermodynamic property enthalpy represents the energy content of the air-water vapor mixture (Btu/lb dry air). In that case, enthalpy accounted for 82% of the variance in judgments of freshness-staleness.

The present investigation reinforces the notion that the comfort of occupants in buildings will depend upon almost all perceptible influences. Temperature and humidity will influence thermal comfort, but they will also influence perception of the chemical quality of the air. The concentration of contaminants will also influence judgments of air quality, but in some instances may actually prove secondary to temperature and humidity. In order to understand how the confluence of physical and chemical properties will jointly determine comfort, it will be necessary to study them jointly.

ACKNOWLEDGMENT

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DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: In the studies with people, was there any consideration for effective temperature or black globe temperature? If so, what were the results? Was there any significant difference between male and female subjects?

L.G. Berglund, John B. Pierce Foundation Laboratory and Yale University, New Haven, CT: The test chamber's design provides very uniform thermal conditions. That is, the air, wall, ceiling, and floor temperatures are very nearly equal. Therefore, for the unoccupied chamber the temperature of a black globe would coincide with the air temperature. When occupied, radiation from the people could raise the black globe temperature slightly (.2° to .5°F) above air temperature, though this was not specifically measured during these tests.

The ASHRAE effective temperatures (ET*) for the sedentary subjects corresponding to the three temperatures and humidities of the tests were:

Ta °F	Tdp °F	ET* °F	Ta °F	Tdp °F	ET* °F	Ta °F	Tdp °F	ET* °F
69.8	36	69.4	75.2	36	74.7	80.6	36	79.5
69.8	52	69.8	75.2	52	75.1	80.6	52	80.1
69.8	68	70.6	75.2	68	75.9	80.6	68	81.5

The data have not been analyzed for response differences between the men and women.

Birgitta Berglund, Department of Psychology, University of Stockholm, Sweden: I noticed that the responses on your perceived scales, e.g., stale-freshness, were given only for a narrow range (2 or 3 units). Do you have some information on

how large your intraindividual variance is in relation to the interindividual variance? This is of importance when you should evaluate perceived scales obtained later for real environments. It will influence the resolution of the scales and thus the possibility to generalize the results. In the real environment there will be many confounding factors that will influence the variance of perceptual scales. Thank you for an interesting paper.

Berglund: Yes, the perceived freshness of the air on a scale of 6 units was about 1.5 units fresher at 70 °F than at 81 °F and a dew point change from 68 °F to 36 °F improved freshness by about .7 units. We have not completed the analysis of variance of the data, so the between- and within-subject variance is not yet available. However, the figures in the paper do give the average standard deviations of the means. For the freshness data, it was 0.25 when the subjects were sedentary, and 0.23 when they walked continuously.

James E. Woods, Honeywell Indoor Air Quality, Golden Valley, MN: Congratulations on an important new set of data presented. Would you please comment on the potential differences of bioeffluents that may have been generated by the subjects' sweating at 36 ° and 68 °F? Could the odors from sweating influence the perceived air quality? In your analysis, will you be able to control for this potential confounding effect?

Berglund: In general, one would expect the generation of bioeffluents to increase with skin moisture from perspiration. The perceived and measured skin moisture of the subjects increased with ambient humidity. Measured skin wettedness under clothing was about 15% higher at the 68 °F dew point humidity than at the 36 °F dew point condition. Further, skin wettedness increased about 10% per Met unit of activity at each environmental condition. The subjects were in each test environment for one hour. If their skin was clean at the onset they may not have had sufficient time to generate any noticeable gaseous bioeffluents from their skin during the test periods. Since the judgment of air quality and the perception of air freshness at the end of each test was nearly unchanged from that at the beginning, it appears that body odor did not contribute to the air quality judgments made by the subjects during these tests. Also, the perceived freshness decreased only slightly with increasing activity.

INDOOR AIR QUALITY, LUNG FUNCTION, AND CHRONIC BRONCHITIS SYMPTOMS IN BEIJING, CHINA—A SURVEY IN THE WINTERTIME

S. Yamaguchi N. Shimojo L. Wang

ABSTRACT

In the authors' first report on the risk factors in chronic obstructive pulmonary malfunction and "chronic bronchitis" symptoms in the Beijing district, it was disclosed that the obstructive lung function was significantly more prevalent in rural areas than in residential and industrial areas (Yamaguchi et al. 1989).

Suspected risk factors that contribute to the occurrence of "obstruction" together with "persistent cough and phlegm"—cigarette smoking, socioeconomic status, and chest illness in the past—were clearly confirmed.

However, the above-mentioned study was carried out in the summertime. The indoor air pollution of rural areas in the wintertime is taken up as one of the hidden risk factors for the obstruction of lung functions.

Health consequences of ambient air and indoor air quality (SO_2, NO_2, SPM) of the "obstruction" and "persistent cough and phlegm" in the present study were not significantly demonstrated. Obviously, an appropriate estimation of the temporality or relationship in time for the justification of a cause-effect relationship is almost impossible, particularly by a cross-sectional epidemiological study.

Results of the present study, however, will be valuable if the accumulation of other data available in such a different but related study and the more reliable epidemiologic findings show similar results.

TABLE 1

ASSOCIATION BETWEEN RISK FACTORS AND "CHRONIC BRONCHITIS" SYMPTOMS OR "OBSTRUCTION"

		"Chronic Bronchitis" Symptoms Adjusted Rate	"Obstruction" Adjusted Rate
Area	Residential	9.08	7.41
	Rural	N.S. 14.72 N.S.	** 21.04 **
	Industrial	16.40	13.37
Sex	Male	13.48 N.S.	13.26 N.S.
	Female	13.62	15.01
Age	40–	13.55	10.53
	50–	N.S. 12.70 N.S.	** 12.24 *
	60+	14.89	22.88 **
SES	High	11.89 **	12.00 **
	Low	16.47	15.77
Past Chest Illness	Yes	22.18 *	19.85 **
	No	5.88	9.07
History in the past (Parent's Resp.Dis)	Yes	16.47 **	15.00 N.S.
	No	12.30	13.78
Smoking	Never	8.52	9.74
	Ex-smoker	** * 12.55 **	** ** 17.44 **
	1 - 9	17.88	17.48
	10+	18.95	17.70

** P < 0.01 N.S. : not significant
* P < 0.05

INTRODUCTION

A cross-sectional epidemiological study on the risk factors in chronic obstructive pulmonary malfunction and chronic bronchitis symptoms in the Beijing district—a joint study between Japan and China—was carried out in August 1986 (Yamaguchi et al. 1989).

Possible risk factors identified that will cause malfunction of the lung, together with chronic bronchitis symptoms, pointed out in the study were cigarette smoking, lower socioeconomic status, and a previous history of chest illness (Table 1). A cross-sectional study can observe only survivors at a certain period of time and subsequent consequences of the cause-and-effect relationship sometimes will be left unsolved.

The China study was carried out in the summer of 1986. Ambient air quality in the Beijing district was available only by GEMS report (Global Environmental Monitoring System), which was published in 1983. The GEMS report did not cover any information on indoor air quality. As a result of the summer 1986 study, it was clear that the obstruction of lung function was significantly more prevalent in rural areas than in industrial and residential areas, where the surrogate ambient air quality regarding sulfur dioxide (SO_2), carbon monoxide (CO), and suspended particulate matter (SPM) was worse than in rural areas (Figures 1-3). If the obstruction of lung function as well as "chronic bronchitis" symptoms can be induced by air pollutants produced by combustion of fossil fuels, indoor air quality in rural areas in the wintertime should be studied because in rural areas in the wintertime, large amounts of coal are consumed for heating and cooking in the houses.

Therefore, in the winter of 1988 (February through March), a series of measurements of SO_2 and nitrogen dioxide (NO_2) were carried out in the houses in a rural Beijing area to determine the present status of indoor air quality (Figure 4). Since the socioeconomic situation has not changed for several years, it is presumed that the lifestyles of rural inhabitants have not changed during this time period. Therefore, it is assumed that the indoor air quality as of February through March 1988 has changed little over the past several years and can be used to estimate the dose retrospectively from the concentration.

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METHOD

Human Subjects

Among samples included in the summer 1986 survey in the Beijing rural area, 42 samples were taken at random—26 males and 16 females—with an average age for males of 53.5 ± 7.0, and for females of 51.8 ± 12.9 years. Human subjects were the members of the 1986 study who have responded with their answers to the British MRC questionnaire (BMRC 1976). They were used for the 24-hour measurement of NO_2 by personal monitoring device and the measurement of SO_2 indoor dose, respectively (Table 2).

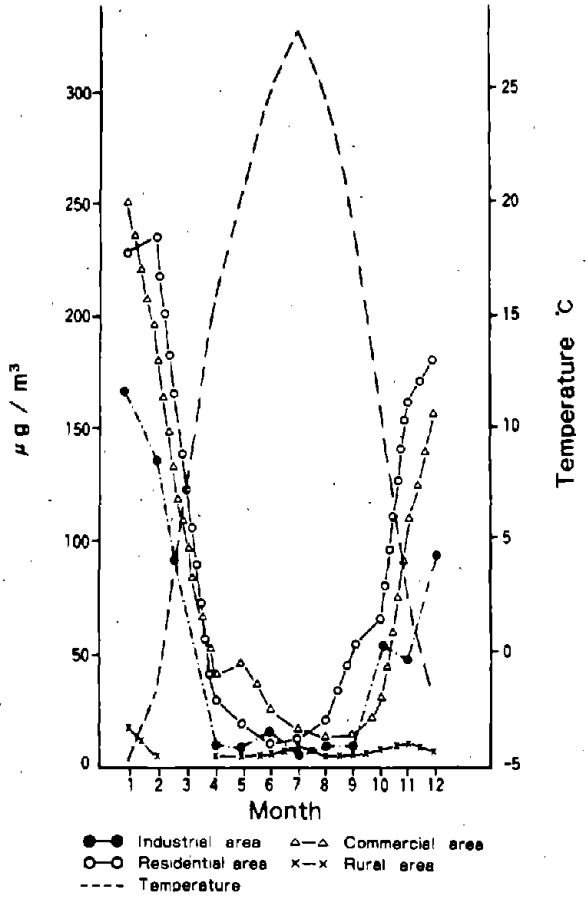

Figure 1 Annual trend of monthly average SO_2 concentration

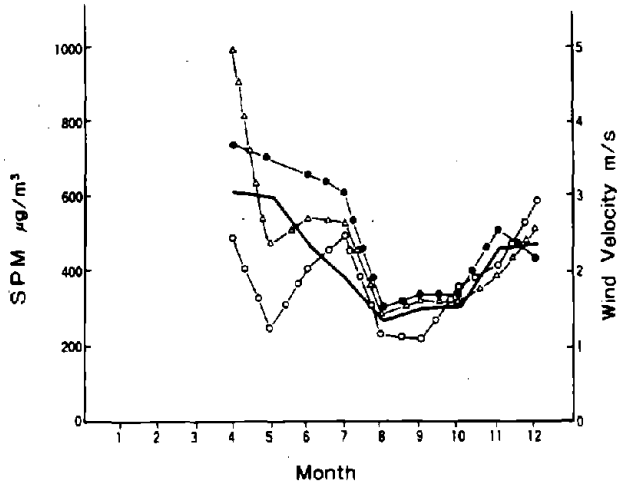

Figure 3 Annual trend of monthly average of SPM in Beijing district (1981)

Measurement of NO_2 and SO_2

For the measurement of NO_2, Yanagisawa's personal sampler was employed (Yanagisawa and Nishimura 1980). NO_2 absorbed in filter paper was determined by a colorimetric absorption method. The reagents used for this method were sulfanilic acid and N-(1-naphthyl)-ethylenediamine 2HCl.

Sulfur dioxide was measured by the alkali-filter paper method (Wang's method). Filter paper soaked with K_2CO_3 was exposed in a room for 24 hours. Then the filter paper was put in a dilute HCl solution. The solution was heated and 10% $BaCl_2$ was added and allowed to stand until the $BaSO_4$ was completely precipitated. $BaSO_4$ was then col-

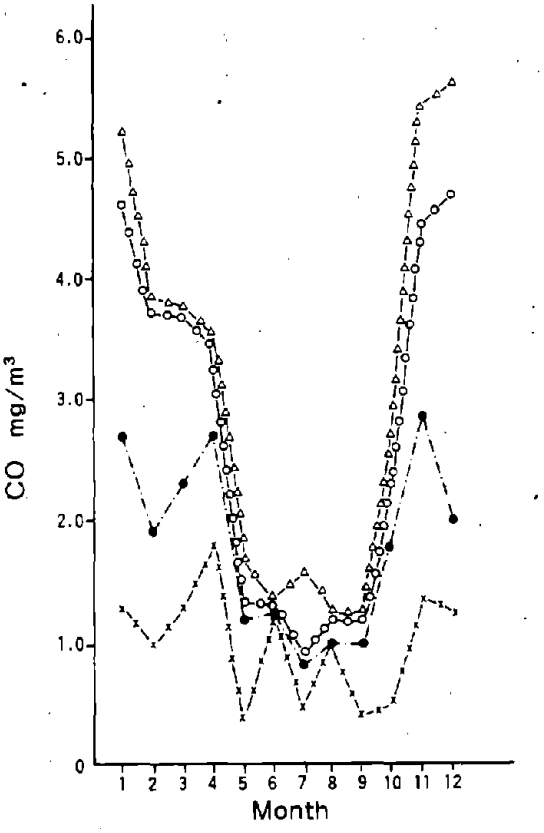

Figure 2 Annual trend of monthly average amount of CO in Beijing district (1981)

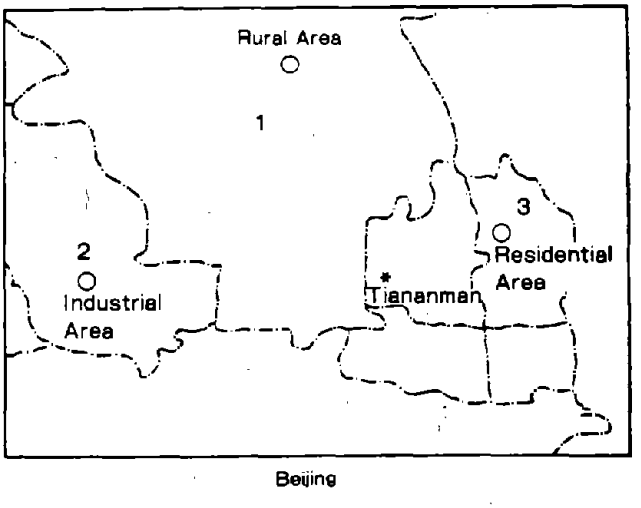

Figure 4

TABLE 2

Relationship between Lung Function, Persistent Cough, Phlegm and Concentration of Indoor NO_2, SO_2

OBS	NO_2 (ppb)	NO_2 (mg/m³ DC)	SO_2 (mgSO₃/100cm²/day)	Q_3Q_6	$FEV_{1.0\%}$	OBSTRUCTION	SEX
1	70.87	0.145	0.753	2	77.2	2	1
2	69.21	0.142	0.537	2	80.0	2	1
3	154.79	0.317	2.421	2	74.9	2	2
4	30.04	0.061	1.365	2	66.8	1	1
5	15.67	0.033	*	1	79.7	2	1
6	148.78	0.305	2.188	2	68.1	2	1
7	114.64	0.235	1.983	2	61.9	1	1
8	156.70	0.322	2.534	2	77.6	2	1
9	303.30	0.621	4.258	2	77.4	2	2
10	100.69	0.207	2.314	2	58.9	1	2
11	71.39	0.146	0.610	2	68.3	2	2
12	85.99	0.177	1.255	4	82.2	2	2
13	189.15	0.388	3.365	4	68.9	2	1
14	200.24	0.411	2.544	2	68.7	2	1
15	193.32	0.396	1.918	2	73.8	2	2
16	86.40	0.177	1.757	2	*	*	1
17	83.69	0.172	0.814	1	66.1	1	1
18	63.69	0.131	1.245	1	51.5	1	1
19	46.94	0.100	0.315	2	84.3	2	1
20	83.31	0.171	5.763	2	69.2	2	1
21	43.63	0.089	0.250	1	72.0	2	1
22	14.74	0.031	0.000	3	84.7	1	2
23	55.00	0.112	1.137	4	84.1	1	2
24	10.63	0.022	0.053	4	80.4	2	1
25	45.80	0.094	0.232	1	41.6	1	1
26	86.70	0.178	0.420	2	77.7	2	1
27	40.17	0.083	0.700	3	71.1	2	1
28	91.68	0.187	1.480	2	45.8	1	2
29	191.58	0.392	7.226	2	80.5	2	2
30	12.96	0.026	0.169	2	89.3	2	2
31	26.03	0.053	1.806	1	57.8	1	1
32	247.03	0.506	3.620	1	74.6	2	1
33	79.92	0.164	3.530	2	75.0	2	2
34	160.94	0.330	6.216	2	73.7	2	1
35	110.06	0.226	*	2	72.6	2	2
36	82.17	0.169	0.622	2	77.8	2	1
37	150.34	0.308	0.979	2	79.1	2	2
38	215.47	0.441	3.051	2	80.9	2	1
39	16.72	0.034	0.099	1	75.7	2	2
40	19.44	0.040	0.397	2	79.9	2	2
41	71.72	0.147	*	2	79.1	2	1
42	108.94	0.223	1.670	4	69.6	2	1

Q_3Q_6 1 (Q_3Q_6 YES) 2 (Q_3Q_6 NO) 3 (Q_3 YES Q_6 NO) 4 (Q_3 NO Q_6 YES)
$FEV_{1.0\%}$ 1 < 68% (OBSTRUCTION) 2 ≥68%
SEX 1 MALE 2 FEMALE

Q_3 Do you cough like this on most days for as much as three months each year (in the winter)

Q_6 Do you bring up phlegm like this on most days as much as three months each year (in the winter)?

TABLE 4

Relationship between indoor concentration of NO_2, SO_2 (wintertime, 1988) and history of persistent cough and phlegm production (summertime, 1986) (Q_3Q_6 BMRC) (Male + Female)

	N	NO_2 (ppb)	N	SO_2 (mgSO₃/100cm²/day)
Q_3Q_6 : yes	8	67.81 ± 76.10	7	1.15 ± 1.25
Q_3Q_6 : no	27	114.96 ± 67.24	25	2.21 ± 1.92
Q_3 : yes, Q_6 : no	2	27.46 ± 17.98	2	0.35 ± 0.49
Q_3 : no, Q_6 : yes	5	89.98 ± 66.52	5	1.50 ± 1.20

Q_3 : Do you cough like this on most days for as much as three months each year (in the winter) ?
Q_6 : Do you bring up phlegm like this on most days as much as three months each year (in the winter) ?
SO_2 : calculated as SO_3

lected by filtration and $AgNO_3$ was added and washed with warm distilled water until Cl^- was removed. Precipitated $BaSO_4$ was then dried at 120° to 130°C and its weight measured. The detection limit by this method is 0.05 mg SO_3/100 cm^2/day. An electroconductivity method was used at the GEMS monitoring station. However, for the Beijing field study this time, the necessary facilities for the the electroconductivity method were not available.

RESULTS

Indoor Air Quality in the Wintertime

Table 3 shows the results of the measurements of the indoor concentrations of NO_2 in the wintertime compared with the summer study. Average NO_2 concentration of samples taken in rural houses was 98.84 ± 70.9 ppb, significantly higher than that of the summer samples (12.46 ± 4.16 ppb).

TABLE 3

Comparison of concentration of NO_2, in ambient and indoor air and $FEV_{1.0\%}$ (Beijing, Rural)

	Mean ± SD	N
NO_2 (winter, indoor)	98.84 ± 70.09 (ppb)	42
NO_2 (summer, indoor)	*12.46 ± 4.16 (ppb)	101
NO_2 (winter, ambient)	48.94 ± 33.86 (ppb)	4
NO_2 (summer, ambient)	15.76 ± 9.89 (ppb)	10
**$FEV_{1.0\%}$ (Male)	71.45 ± 10.62 %	25
**$FEV_{1.0\%}$ (Female)	72.28 ± 9.87 %	16
**$FEV_{1.0\%}$ (Male + Female)	71.77 ± 10.22 %	41

* : Test of Difference : winter vs. summer, indoor, $P < 0.01$
**$FEV_{1.0\%}$: Less than 68% of $FEV_{1.0\%}$ summertime study.

TABLE 5

Relationship between indoor concentration of NO_2, SO_2 (wintertime, 1988) and $FEV_{1.0\%}$ (Male+Female) (summertime, 1986)

	N	No_2 (ppb)	N	SO_2 (mgSO₃/100cm²/day)
1 : $FEV_{1.0\%} < 68$	10	82.66 ± 34.19	10	1.24 ± 0.73
2 : $FEV_{1.0\%} > 68$	31	*110.91 ± 75.97	28	2.05 ± 1.98

*Test 1 vs. 2 : $P < 0.05$
obstruction : < 68% one second percent of FEV
SO_2 : calculated as SO_3

while the concentration in ambient air was not significantly higher than that of the summer (48.94 ± 33.86 ppb: winter vs. 15.76 ± 9.89 ppb: summer).

According to the GEMS report, the concentration of SO_2 in ambient air in the rural area (1981) near Beijing was 21 g/m³ in the winter (January) and 6 g/m³ in the summer (July).

Indoor Air Quality and Health Effects

As far as the relationship between the persistent cough and phlegm production in addition to the obstructive lung function among inhabitants in rural areas and indoor air quality (NO_2, SO_2) is concerned, as was shown in Tables 4 and 5, a significant correlation or dose response relationship was not observed.

CONCLUSION

In general, the use of air quality standards for ambient air assumes that some level of both emissions and concentration of pollutants is permissible, with both low enough so as not to cause significant health effects.

However, except in extraordinary episodes, like the London episode in 1952, when 4000 excess deaths were estimated among inhabitants in the greater London area who may have been exposed to 4460 g/m³ SPM and 3830 g/m³ SO_2 (highest 24-hour values) (data from the British Ministry of Health) (Lawther et al. 1970; Ministry of Pensions and National Insurance 1965), no data were obtained on the critical concentrations of many chemical pollutants in ambient air at which adverse health effects are precisely evident (i.e., not as subjective complaints but as clinical findings obtained by the best medical diagnostic techniques).

If contamination has occurred by multiple noxious agents, the degree of contribution of each substance to the health consequences postulated will not be clarified.

In this study, as far as the consequent health effects are

concerned in the environment containing NO_2 and SO_2 at the concentrations mentioned above, no definite conclusion could be afforded. Risk factors other than chemical air pollutants and their degree of probability found in the summer study will be discussed elsewhere.

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DISCUSSION

Carl N. Lawson, LRW Engineers, Tampa, FL: Do you find any stress-related problems in your lung studies?

S. Yamaguchi, Institute of Community Medicine, The University of Tsukuba, Japan: It depends upon the nature of "stress." However, we did not feel any "stress" in our study.

INDOOR AIR QUALITY IN 12 SCHOOLS: A CASE STUDY

D.M. Cousins C.W. Collett

ABSTRACT

An investigation of indoor air quality in 12 schools in Alberta was conducted to evaluate the relationship between type of ventilation system, occupant health and comfort, and levels of specific indoor pollutants. Three categories of schools were investigated: (1) schools constructed prior to 1960 with no modification to mechanical systems, (2) schools constructed prior to 1960 which have been upgraded to meet current building codes, and (3) schools constructed since 1960.

A questionnaire survey was administered to teachers, administrators, and custodial staff. Common health and comfort complaints reported by occupants of all school types included: headache, fatigue, eye irritation, sore throat, too little air movement, stuffiness, and poor temperature control. The highest prevalence of health and comfort complaints were reported by occupants of schools constructed since 1960.

Based on the results of the questionnaire, three schools (one from each category) were selected for further evaluation of air quality parameters by physical measurement. Carbon monoxide, respirable particles, temperature, relative humidity, and airborne microbial levels were similar in all three schools and were far below established air quality guidelines. However, carbon dioxide (CO_2) concentrations varied substantially within and between schools, exceeding, at times, 1000 ppm in classrooms of each school. The highest CO_2 concentrations (2000 to 2800 ppm) were measured in portable classrooms. The elevated CO_2 concentrations indicate that the ventilation systems, as operated, were ineffective in meeting the outside air requirements. Total outside air requirements in classrooms are greater than for other areas within the schools because of the high density of students.

Recommendations to improve indoor environmental conditions in the three schools included an overhaul of outside air dampers, relocation of supply air registers, and continuous operation of ventilation systems during occupancy of portable classrooms.

INTRODUCTION

An investigation of indoor air quality in 12 schools in Alberta was conducted to evaluate the relationship between age of construction, type of heating and ventilation system, occupant health and comfort, and levels of specific indoor pollutants. The study was conducted during March and April 1988.

Twelve school buildings, representing specific age groups and types of mechanical systems, were chosen for the study. The chosen schools were typical of many schools in the province of Alberta. The 12 schools were categorized into three types:

1. Old: Construction prior to 1960, with no modifications to the original heating and ventilating systems.
2. Renovated: Construction prior to 1960, with heating and ventilation system upgrades to current building codes.
3. New: Constructed since the early 1970s, representing a modern, "tighter" approach to building technology.

METHODS

The study utilized a phased approach for building performance evaluation, which has previously been used in field evaluations of offices and other public buildings in North America and Great Britain (Sterling et al. 1987). The approach provided a time- and cost-effective means of evaluating the schools.

Phase One

Phase One consisted of a review of each of the 12 schools' architectural and mechanical systems design, operation, and maintenance practices.

The major architectural components of the buildings were reviewed and identified. The age of construction, the type of interior finish, floor covering, type of windows, etc., were examined for sources of indoor air contaminants.

The heating and ventilation systems were reviewed in detail. The method of delivering supply air to, and removing return and exhaust air from, a typical classroom was identified. The location of outdoor air intakes was compared to the location of the discharge from return and exhaust fans, to evaluate the potential for re-entrainment of fumes.

Phase Two

Phase Two, also carried out on all 12 schools, consisted of the administration of a "Work Environment Survey" questionnaire to building occupants (teachers, administrators, and custodial personnel, but not students) to quantify the type and extent of the environmental comfort problems and health-related symptoms experienced by occupants.

The Work Environment Survey is a self-administered, machine-readable questionnaire that has been used previously to survey occupant perceptions in offices and other public buildings.

The questionnaire is designed to obtain three categories of information:

1. Demographic and occupational characteristics of the building occupants, for example, age, sex, educational background, and job type.
2. Occupant perceptions of satisfaction and dissatisfaction with indoor environmental conditions, including air movement, humidity, temperature, lighting, and noise conditions.
3. Occupant perceptions about health-related symptoms. The health symptoms are divided into two general groups—one that has been frequently related to poor air quality and the "sick building syndrome," and one that is not directly related to air quality, but more to stress factors in the workplace.

The Work Environment Survey is designed to determine the frequency of response to each health and comfort question using a four-point scale of "never," "rarely," "sometimes,"

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or "always." For the purposes of data analysis, the "sometimes" and "always" were combined to provide indication of the most prevalent health and comfort complaints.

Based on the results of Phases One and Two, three schools were selected (one each from the Old, Renovated, and New categories) for continued evaluation in Phase Three.

Phase Three

Phase Three was a detailed indoor air quality evaluation, carried out in the three selected schools. Measurements were taken at sampling sites throughout each school building and at an outdoor site.

The following indoor air quality parameters were measured in each school:

1. Carbon dioxide (CO_2) as an indicator of ventilation adequacy. CO_2 was measured using direct-reading colorimetric detector tubes and a portable digital readout infrared analyzer.
2. Carbon monoxide (CO) as an indicator of combustion byproducts, such as automobile exhaust infiltrating from outside the building or from gas-fired appliances. CO was measured with a portable electrochemical analyzer.
3. Temperature and relative humidity as indicators of occupant thermal comfort conditions in the schools. These parameters were measured using a digital readout indicator equipped with a fast response electronic probe.
4. Respirable suspended particles (RSP) as an indicator of the efficiency of ventilation filtration systems, general cleanliness, and the presence of environmental tobacco smoke. RSP concentrations were determined using a light scattering monitor equipped with a five-micron impactor.
5. Total fungi and bacteria as indicators of airborne microbial loading. Microbial samples were collected with an Anderson sampler using methods recommended by the American Conference of Governmental Industrial Hygienists (ACGIH Committee on Bioaerosols 1986). Bacterial samples were collected on trypticase soy agar and fungal samples were collected on rose bengal agar.

Each school was visited for one day. Two sets of measurements for CO_2, CO, temperature, relative humidity, and RSP were taken at each sampling site in each of the three schools. One set of measurements was taken during the morning and a second set during the afternoon. Total fungi and bacteria were measured at at least one indoor site and one outdoor site at each school.

RESULTS

Phase One

Architectural and mechanical design and mechanical system operation and maintenance were reviewed in all 12 schools during February 1988. Although the schools in each category—"old," "renovated," and "new"—varied in architectural and mechanical design, the three schools later selected for detailed evaluation may still be considered "typical" and therefore representative of their school type.

The "old" school was constructed between 1949 and 1954 and is of wood frame construction with a crawlspace and built-up flat roof. Heating is provided by two steam boilers and is distributed to perimeter radiation and unit ventilators in each classroom. Each classroom has a thermostat. Ventilation is provided by operable windows and unit ventilators. General exhaust fans are located in corridors and cloakrooms. The exhaust fans and unit ventilators were not operating during the indoor air quality evaluation because teachers find them too noisy to run continuously. Consequently, they are only operated in extreme winter conditions. The school does not have a humidification system.

TABLE 1

Responses to Environmental Questions: 12 Alberta Schools

Environmental Conditons	4 Old Schools (n = 126)	3 Renovated Schools (n = 58)	5 New Schools (n = 146)
	% Sometimes or Always		
Air Movement			
Too Little	61.9	63.8	75.3
Humidity			
Too Dry	84.9	77.6	93.8
Air Quality			
Too Stuffy	65.1	70.7	86.3
Unpleasant Odors	55.6	36.2	58.9
Temperature			
Too Hot	73.8	74.1	85.6
Too Cold	64.3	58.6	74.0
Lighting			
Too Bright	23.8	15.5	28.8
Too Dim	26.2	12.1	26.7
Noise			
Too Noisy	69.0	65.5	66.4

TABLE 2

Responses to Health Questions: 12 Alberta Schools

Symptoms	4 Old Schools (n = 126)	3 Renovated Schools (n = 58)	5 New Schools (n = 146)
	% Sometimes or Always		
Headache	54.0	46.6	71.2
Fatigue	73.8	26.0	78.1
Sleepiness	47.6	43.1	62.3
Eye Irritation	38.9	31.0	53.4
Sore Throat	46.0	39.7	60.9
Nose Irritation	44.4	32.8	56.2
Cold/Flu	53.2	41.4	52.1
Skin Dryness	49.2	46.6	44.5
Backache	38.9	41.4	41.1
Neckache	28.6	32.8	46.6
Tension	40.5	41.4	47.3

The "renovated" school was originally constructed in 1953, with subsequent additions in 1956, 1957, 1960, and 1985. In 1985, the school was completely modernized. The school is a combination wood frame and masonry construction with slab on grade. Heating is provided by two hot water boilers and distributed by wall fin radiation. Ventilation is provided by four air-handling units. Air is distributed to perimeter classrooms through under-slab ductwork that was reused during renovation. Air is distributed through ceiling-based systems to the gym, library, and administrative areas. Each air-handling unit is equipped with a pan humidifier.

The "new" school was constructed in 1980 and is masonry with slab on grade. In addition, six wood-frame portable classrooms are attached to the main school building. Heat is provided to the main school by two hot water boilers that serve perimeter radiation. A thermostat is located in each classroom. Additional heating to interior areas is provided

by reheat coils in the ventilation system. Ventilation is provided to classrooms by a central ventilation unit. The gym and auditorium/lunchrooms have separate ventilation units. Air is delivered to the spaces through ceiling-based systems. Each unit has steam humidification, which was not operating during the air quality tests.

The portable classrooms attached to the new school are heated and ventilated by residential-type furnaces. The furnace fans are set for intermittent operation and would only operate when heating is required (i.e., non-continuous operation). The portable classrooms are not humidified.

Phase Two

Following the architectural and mechanical review of the 12 schools, the "Work Environment Survey" questionnaire was administered to teachers, administrative, and custodial staff in each school. Tables 1 and 2 summarize the results for each "group" of schools.

Table 1 shows the most prevalent complaints about indoor environmental conditions. The table shows the percentage of respondents in each type of school who reported that the particular environmental conditions "sometimes" or "always" occurred at work. The pattern of response was similar for all three types of schools with the most prevalent problems reported as too little air movement, air too dry and too stuffy, and fluctuating temperatures. Lighting was not perceived to be a problem. However, more than 60% of the occupants of all schools reported that it was sometimes or always "too noisy," a complaint consistent with noisy students! Although the pattern of response was similar for all three categories of schools, the most prevalent complaint was generally reported in the new schools, as illustrated in Figure 1. As the six environmental parameters show, occupants of the new schools reported the highest prevalence of complaint.

Table 2 shows the most prevalent health symptoms reported by occupants of each category of school. The pattern of symptoms reported in all three school categories was similar. The most prevalent health complaints included: headache, fatigue, eye irritation, sore throat, nose irritation, colds/flu, and skin dryness. This symptom complex is similar to the types of health complaints typically associated with sick building syndrome (Stolwijk 1984).

Symptoms not generally associated with sick buildings, such as backache, neckache, and tension, were also similar in all three school categories. These symptoms are more stress-related. The prevalence rates found in the schools are generally higher than have been found in office buildings using the same questionnaire survey, suggesting a perceived high level of workplace stress in the teaching profession.

Figure 2 illustrates the comparative prevalent rates in the three types of schools for the most commonly reported symptoms. For the six symptoms shown, occupants of the new schools reported the highest rate of complaint. Occupants of the renovated schools reported the lowest rate of symptoms.

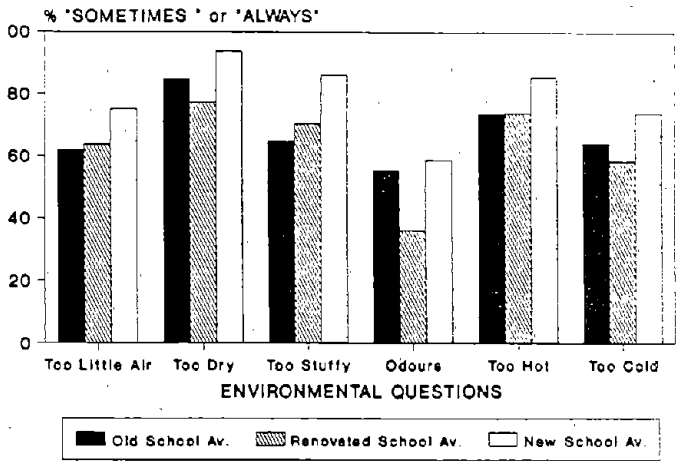

Figure 1 Environmental question responses—school category averages

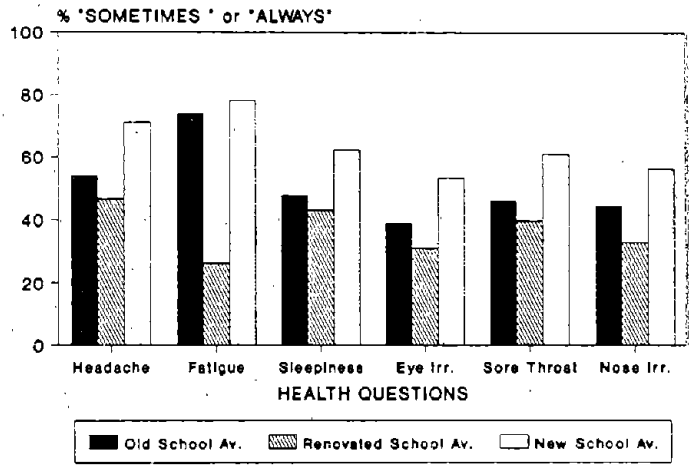

Figure 2 Health question responses—school category averages

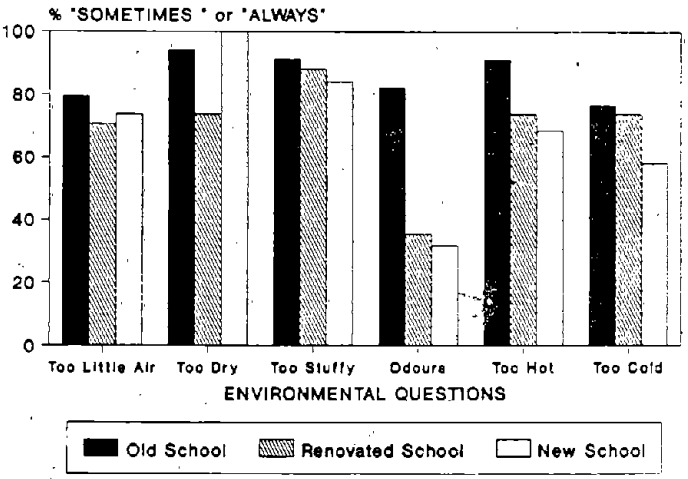

Figure 3 Environmental question responses—schools selected for Phase Three

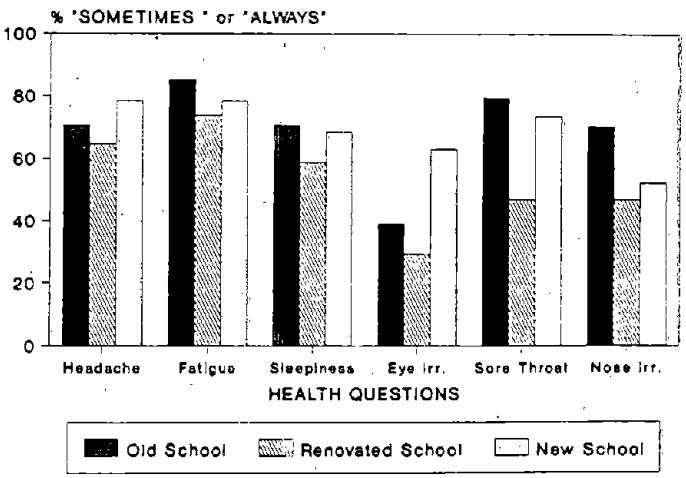

Figure 4 Health question responses—schools selected for Phase Three

TABLE 3

Mean and Ranges of Measured Indoor Air Quality Parameters: Three Alberta Schools, March 1988

	Old School	Renovated School	New School	Portable Classrooms
Carbon Dioxide (ppm)	750 (500–1100)	750 (550–1400)	650 (500–900)	1950 (1000–2800)
Outdoor	350	400	350	350
Carbon Monoxide (ppm)	1.3 (1.0–1.8)	1.1 (0.7–1.5)	0.9 (0.7–1.1)	0.9 (0.8–1.0)
Outdoor	2.1	11.5	1.1	1.1
Temperature (°C)	22.8 (21.6–24.8)	22.6 (21.3–24.8)	22.9 (22.5–23.8)	23.6 (23.2–24.1)
Outdoor	8.6	3.5	6.3	6.3
Rel. Humidity (%)	14.2 (11.3–17.8)	18.6 (13.8–27.2)	17.1 (15.3–21.3)	26.6 (24.1–31.2)
Outdoor	23.6	39.9	38.5	38.5
Resp. Particles ($\mu g/m^3$)	16 (11–22)	13 (10–20)	14 (10–17)	17 (15–20)
Outdoor	23	15	18	18
Total Bacteria (cfu/m^3)	386 (230–489)	137 (129–145)	388 —	—
Outdoor	486	202	106	—
Total Fungi (cfu/m^3)	175 (89–269)	98 (55–141)	56 —	—
Outdoor	150	78	51	—

In addition to analysis of questionnaire responses for each category of schools, individual school responses were analyzed to select one school from each group for further evaluation. The "worst case" school (i.e., that with the highest rate of health and comfort complaints) from each category was chosen. Figures 3 and 4 show the questionnaire responses for the most prevalent complaints in the "worst case" schools. A lack of air movement, dryness, and stuffiness were the prevalent comfort problems in all three schools, with the highest reported problems in the old school. Occupants of both the old and new schools reported similar rates of health complaints. Prevalence rates for the health symptoms were slightly lower in the renovated schools.

Phase Three

The findings from the indoor air quality evaluations undertaken in the three selected schools are shown in Table 3. For each air quality parameter, the mean level, range of values (in parentheses), and outdoor levels are given. Data are also shown for the portable classrooms attached to the new school.

Carbon dioxide concentrations were lowest in the new school, ranging from 500 to 900 parts per million (ppm). CO_2 levels in the old and renovated schools were highest in occupied classrooms, exceeding the 1000 ppm level used to indicate "adequate ventilation" in ASHRAE Standard 62-1989 (ASHRAE 1989). By far the highest CO_2 concentrations found in the three schools were in the portable classrooms. All measured values exceeded 1000 ppm, with a maximum of 2800 ppm. The elevated CO_2 concentrations in occupied classrooms in all schools illustrated the particular demands placed on mechanical systems by a high density of students. Only the mechanical systems in the new school were able to cope with such demands. In the old and renovated schools and in the portable classrooms, the outside air delivery was inadequate to meet occupant requirements.

Carbon monoxide concentrations were low in all schools. Indoor levels were generally lower than outdoors, indicating that neither the infiltration of fumes from outdoors nor combustion byproducts from gas-fired equipment was a problem.

Mean temperature levels were similar in all three schools (between 22°C and 23°C), despite outdoor variations. There was a wider variation in indoor temperatures within the old and renovated schools, compared to the new school. To assess the impact of the measured temperatures upon occupant comfort, the results can be compared to the comfort range defined in ASHRAE Standard 55-1981, "Thermal Environmental Conditions for Human Occupancy," which defines a winter comfort range of 19°C to 24.5°C (ASHRAE 1981). Almost all temperature measurements in the three schools were within this comfort range. There were only two exceptions—one classroom in each of the old and renovated schools.

The relative humidity levels found in the three schools can also be compared to the 20% to 80% range of comfort defined by ASHRAE Standard 55-1981. Mean relative humidity levels in all three schools were below 20%. Additional research conducted for Health & Welfare Canada has suggested that 40% to 60% relative humidity would be optimal for human comfort (Sterling et al. 1985). The low humidity levels in the schools correspond with the prevalence of occupant-reported problems of "air too dry" in Phase Two.

Respirable particle concentrations were similar in all three schools, ranging from 10 to 22 micrograms per cubic meter ($\mu g/m^3$). Indoor levels were generally lower than outdoors. The low RSP concentrations indicate effective filtration and good janitorial practices in the schools.

Airborne microbial concentrations were highest at the old school, with a total bacterial concentration of 386 colony-

forming units per cubic meter (cfu/m³), and a total fungal level of 175 cfu/m³. However, outdoor concentrations were also highest at the old school. Air quality standards have not been established for airborne microbes. However, research by Morey (1984) has suggested that microbial concentrations in excess of 1000 cfu/m³ indicate possible microbial contamination and warrants further investigation. All microbial concentrations in the three schools were well below the 1000 cfu/m³ level of "concern."

DISCUSSION

The findings from the study of the 12 schools clearly shows that occupants of schools experience similar indoor environmental problems to office workers. The survey showed a complex array of health and comfort complaints that have been commonly reported in other office and public buildings. A higher prevalence of health and comfort problems was reported by occupants of new schools (built using modern, tight construction technology) when compared to old and renovated schools. However, the subsequent measurements showed few differences between the indoor air quality in the three types of schools. In each of the old, renovated, and new schools, measured parameters were within established guidelines, with the exception of CO_2. Using a CO_2 concentration of 1000 ppm as an indicator of ventilation adequacy, inadequate delivery of outside air was found in classrooms in the old and renovated schools and also in the portable classrooms attached to the new school. The high CO_2 levels in classrooms suggests that the human-generated CO_2 in occupied classrooms is not being controlled by the ventilation systems. A consequence of ventilation-related problems in the schools is the high rate of complaints such as a lack of air movement and stuffiness, which may also be linked to health symptoms such as headache, fatigue, and sleepiness.

The Phase One evaluation (review of plans and inspection) showed possible deficiencies in the heating and ventilation systems in each school. The impact of these deficiencies on occupant health and comfort was determined in the subsequent questionnaire surveys.

Based on the findings of the overall evaluation, recommendations were made to improve the function of the mechanical systems, which in turn would have a positive effect on the indoor environment. Recommendations included overhaul of the unit ventilators in the old school and consideration of system redesign, relocation of supply air registers in the renovated school to improve air distribution, and ductwork modification and acoustical treatments in the portable classrooms to allow continuous operation of the furnace circulation fans.

ACKNOWLEDGMENT

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DISCUSSION

Carl N. Lawson, LRW Engineers, Tampa, FL: How did you handle the CO-CO_2 in these schools?

D.M. Cousins, Keen Engineering Co. Ltd., Vancouver, BC, Canada: CO and CO_2 (and respirable particles, temperature, and relative humidity) were measured once in the morning and once in the afternoon at locations throughout the schools (classrooms, labs, staff rooms, library, offices) and at one outdoor site.

Lawson: With your outside air intakes located in the side of the penthouse, weren't you concerned about contaminants from the rainwater build-up being brought into the HVAC system? Also, why not put outside air intakes on-roof with goosenecks?

Cousins: The velocity of the outdoor air is kept below 500 ft/min so that there is virtually no entrainment of moisture or dust. Architects do not generally like goosenecks on the roof and we try to keep them to a minimum.

James E. Woods, Honeywell Indoor Air Quality, Golden Valley, MN: On what basis can you conclude that the air quality was "acceptable" given the high frequency rates of complaints you reported?

Cousins: The conclusion of "acceptability" was based upon comparison of the physical air quality measurements with available air quality standards. Certainly, the high frequency of complaints would suggest that the air quality may not have always been "acceptable" over the period of recall for the questionnaire (six months).

Ed Light, Biospherics Inc., Beltsville, MD: What were the times and location of the samplings?

Cousins: As mentioned, CO, CO_2, RSP, temperature, and relative humidity levels were measured at locations throughout the schools, twice during the day of sampling—once in the morning and again in the afternoon. Airborne microbial samples were collected at two or three locations in each school and also at an outdoor site.

MANAGING AN INDOOR AIR QUALITY (IAQ) PROBLEM IN A PUBLIC BUILDING

Emerson L. Besch, Ph.D. *ASHRAE Member*
H. Jean Besch, M. Ed.

ABSTRACT

Indoor air quality (IAQ) and building-associated illness (BAI) are not new and much has been reported in the literature about these problems, the criteria that distinguish "sick" from "healthy" buildings, remedial actions that restore building function as originally intended, and efforts to ensure the health and comfort of building occupants. What has been overlooked, however, are two other important issues: first, that IAQ problems constitute institutional crises and should be managed as such and, second, that in the management of the crisis, the health and comfort of the manager can be as adversely affected—through crisis-induced stress—as that of the occupants. The longer it takes to identify the antecedents of the problem and institute corrective action, the more likely the performance, productivity, and morale of everyone, including the manager, will be unfavorably affected. Most of these adverse consequences can be avoided if the manager accepts the notion that IAQ problems constitute crises and that crisis-management techniques are the most effective means of dealing with the situation as well as the health and comfort concerns of the occupants. The manager is particularly challenged if the IAQ problem becomes bound with bureaucratic "red tape" so often found in public agencies. In that case, implementation of crisis-management strategies, although imperative, may be difficult.

INTRODUCTION

Much has been reported in the literature and at conferences about indoor air quality (IAQ) and building-associated illness (BAI), remedial actions necessary to restore building function as originally intended, and efforts to ensure the health and comfort of building occupants. Individuals who have been personally involved recognize that managing the events related to an IAQ problem involves more than merely establishing the criteria that differentiate a "sick" from a "healthy" building and introducing corrective actions. Yet, little information is available regarding either the perspective of the "the middle manager," who must deal with these issues, or specific advice on how to manage during turmoil.

The authors suggest that while IAQ problems, particularly Sick Building Syndrome (SBS), are special, with no two case studies being identical, they have at least two commonalities besides non-specificity of symptoms—1) IAQ problems constitute institutional crises and should be managed as such; and, 2) in the management of those crises, the health and comfort of the manager can be as adversely affected—through crisis-induced stress—as that of the building occupants.

In addition, should the manager not possess sufficient understanding of the essence of IAQ problems or, perhaps more importantly, the requisite authority for decisive action, a timely resolution of the problem will not be forthcoming. The longer it takes to identify the antecedents of the problem and institute corrective action, the more likely it will be that the performance, productivity, and morale of everyone—including the manager—will be unfavorably affected. The manager is particularly challenged when the IAQ problem becomes bound with the bureaucratic red tape so often found in public agencies. In that case, implementation of crisis-management strategies, although imperative, may be difficult.

PUBLIC INSTITUTIONS AS BUREAUCRACIES

Although the intention of a bureaucracy is to achieve objectives with efficiency, the perceived slowness in response and resistance to change often are criticized as "red tape" (Lanford 1981). The impersonal nature of a bureaucracy results partly from controls, restrictions, or requirements which were designed for a purpose, often to protect citizens from harm (Kaufman 1977). It has been suggested that lagging responses may be advantageous because they tend to prevent drastic actions pursued by extremists (Jansen 1978). Nonetheless, even successful programs or institutions have been criticized for their red tape when they are excessively slow in their actions (Kaufman 1977).

The bureaucratic approach often is equated to public agencies, which are characterized by their central administration (Kharbanda and Stallworthy 1986). While bureaucracies may seem to be impersonal and antidemocratic, the character of an organization is determined by the persona of its management and criticisms of bureaucracies conceivably result more from human behavior than the organization per se. That is, if a bureaucracy does not function, it may be the fault of the managers and staff, not the hierarchical structure (Lanford 1981). Managers who do not maintain a direct involvement at all levels of operations and two-way communications risk being overwhelmed by the unexpected (Meyers and Holusha 1986).

Nothing unsettles a bureaucracy more than uncertainty and, when exposed to unexpected trouble or crises, bureaucrats generally respond by going through characteristic stages (Fink et al. 1971). This is because bureaucracies generally develop conformity, overlook informal organization, and provide the bureaucrat (i.e., crisis manager) with little flexibility of action in dealing with crises (Lanford 1981). These observations have led to the suggestion that bureaucrats should not manage projects because those projects would be ". . . doomed from the start" (Kharbanda and Stallworthy 1986).

RECOGNIZING IAQ PROBLEMS AS CRISES

Indoor air quality problems often develop into crises which, by definition (Webster 1986), are ". . . turning points for better or worse; situations that have reached the critical phase." If not controlled, crises may escalate in intensity, come under close media or government scrutiny, interfere with normal business operations, jeopardize the positive pub-

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TABLE 1

Stages and Outcomes of Managed and Unmanaged Crises

Stages of Crisis	Outcomes: Managed	Outcomes: Unmanaged
Pre-crisis	Evidence, acknowledgement, resolve	Non-performance, denial, anger
Crisis	Climax, assessment, direction	Failure, panic, collapse
Post-crisis	Rebuilding, recovery, reform	Shock, radical change

From: Meyers and Holusha, 1986

lic image of the company or entity, and damage the company's "bottom line" (Fink 1986). Consequences of crises include general uncertainty, multiple and simultaneous problems, need for extraordinary resources, time constraints, stress, change in power structures, and change in communication patterns (Jung 1979).

In the process of verifying that the complaints constitute valid building-associated illness, the manager likely will be faced with anxious occupants who, perceiving they have been exposed to an occupational health risk and potential post-exposure health problems, pressure for a quick solution to the problem. These individuals expect the manager to provide a speedy, but effective, solution while higher authority may remain skeptical about whether a "real" problem exists. These conflicting views may result not only in limited or no action but also contribute to increased frustration in both managers and occupants. The frustration may intensify and turn to anger if the IAQ problem is not remedied quickly.

Public institutions often are incapable of responding rapidly even when managers are sympathetic to the needs and concerns of employees (i.e., providing a safe and secure workplace) in a manner consistent with fulfillment of institutional goals. Reminders that a public agency is a bureaucracy, fraught with red tape, are likely to fall upon deaf ears. Cutting red tape means expediting solutions but bureaucracies often respond slowly (Kharbanda and Stallworthy 1986). This is partly because the ability to cut red tape may not be within the grasp of first-line administrators (i.e., they are not empowered to cut red tape and therefore cannot deal with problems expeditiously) and partly because higher authorities also must be sensitized to and agree that an IAQ problem exists and that their assistance is required in the solution. While strategies may differ between private- and public-sector buildings, solutions for IAQ problems appear to involve crisis-management strategies in both public and private organizations.

ESSENTIALS OF CRISIS MANAGEMENT

Stages of Crisis

Crises emerge in definable stages but outcomes vary depending upon whether the crisis is managed or unmanaged (Table 1). When crises are unmanaged, the warnings of the pre-crisis period are either undetected or unheeded and this results in objectionable consequences of the crisis and post-crisis stages: obvious failure, attendant publicity, panic, and collapse (Fink 1986). However, even if the warning signs go undiscovered, in a well-managed crisis all actions through the crisis stage are expedited to ensure an early resolution (Fink 1986).

In the pre-crisis stage there is a perception that something is wrong (i.e., lowered productivity, increased worker complaints) but uncertainty about what is causing the problem. Because the problem usually is not visible to the outside world, it is during this period that detection and intervention will do the most good. In the second—or crisis—stage, the outside world is aware of the problem, all employees are affected, there is a loss of common purpose and cohesiveness, information is biased by emotion, available data are subject to multiple interpretations, infighting begins, and decisions are debated/challenged rather than obeyed. Should the crisis continue uncontested, the last stage—or post crisis—is characterized by shock, uncertainty, and radical change. It is particularly difficult for managers in public agencies because any failure that is perceived to affect the public usually brings about increased scrutiny and regulation (Meyers and Holusha 1986).

Many buildings with complaints thought to be related to indoor air problems have been investigated by industrial hygienists and others who could detect no variance with industrial standards. Rather than concluding that a problem may exist even though the building met standards, the building manager may conclude that no problem exists. Unfortunately, the consequence of this type of response only delays recognition of the pre-crisis stage and initiation of meaningful intervention.

Identifying the Crisis

The sooner the symptoms of crisis stages can be discerned, the sooner they can be dealt with in a timely manner (Slatter 1984). However, recognition that crises exist may be complicated by the fact that they often are accompanied by other problems (Fink 1986). This is particularly so for crises that result from IAQ problems because of the non-specific symptoms of SBS or BAI and the fact that managers often do not possess sufficient understanding of the problem to make an early diagnosis. All of these considerations may delay, but should not prevent, identification of the real crisis, which may be accomplished by applying questions such as: Will the situation escalate if left unattended? Will it promote unwanted media attention? Will it interfere with normal business procedures/programs? If the answer is yes to any of these, there is a high probability that the crisis has been identified.

An example of delay in problem recognition and timely resolution is the Texas public school building in which a number of health problems were alleged to be caused by a distinctive odor that was detected when the building was new and persisted for the next nine years (Winfield 1987). While many individuals initially viewed the problem as a nuisance or a joke, some parents believed that the symptoms (fatigue, nausea, sore throat, eye and nose irritation, headache, and stomachache) experienced by their children were caused by the odor. The Texas Department of Health was asked to investigate the problem three times over a four-year period and, although each time it reported that no health hazards had been found, the complaints persisted. The odor problem (caused by the integral styrene-butadiene synthetic rubber backing of the carpet) was finally resolved because of the persistence of concerned parents who formed a community action group and invited the local press to their meetings (Winfield 1987).

Isolating the Crisis

Crises, like communicable diseases, cannot be cured through inattention (Meyer and Holusha 1986). Although an IAQ crisis may encompass only part of a building, unless it is isolated its consequences can affect the whole organization. That is, all employees may react to the crisis through loss of common purpose and cohesiveness or development of fuzzy, conflicting goals. Those consequences can be avoided by appointing a crisis manager who is authorized to make financial decisions and who perceives the needs of employees and the institution. That individual must be able to communicate with workers and motivate them to achieve institutional goals (Dyer 1978).

The consequences of failing to effectively communicate and isolate a crisis are apparent from the report of an acute indoor air pollution problem associated with renovations in a city office building (Lee et al. 1987). Renovations of the basement of a 40-year-old, six-story building resulted in reports of symptoms such as headache, nosebleeds, coughing, and tachycardia. Although the health department had investigated these employee complaints, the resultant recommendations either were partly ignored or bypassed. This, together with poor communications between contractors and building occupants and between management and employees, exacerbated the problem, caused increased complaints, and ultimately affected three departments before corrective action was implemented (Lee et al. 1987).

Managing the Crisis

While the manager may identify and isolate the problem, resolution may be delayed because, in a bureaucratic organization, additional layers of management must be sensitized to the nature of the problem and establish the necessary prioritization for successful remediation. Clearly, the manager is placed in a pressure situation, one that he or she may not be prepared to handle. Retreating behind closed doors and avoiding confrontation and problem resolution only serves to further exacerbate the situation.

An example of timely and effective corrective action regarding an indoor air problem involves a large-vehicle storage building in which a need for improved ventilation was perceived to be related to symptoms (headache, eye irritation) of employees caused by odors and a high concentration of polluted air emitted by the vehicles (Curnew 1988). In keeping with a general department policy of improving indoor air quality in practical, but energy-conserving ways, a solution for detecting and removing polluted air was developed for the vehicle storage building and also later applied successfully to other buildings.

THE CRISIS MANAGER

Unanticipated events—and IAQ problems fit into this category—augment the potential for crisis and it is the middle manager (Table 2) who often is called upon to manage the crisis. It is reasonable to assume that this increases the complexity of the manager's workload and, while conflict and ambiguity represent a measure of challenge, they also cause stress and impaired performance (Broussine and Guerrier 1983). Even though the climate of the organization may determine whether the manager utilizes a proactive or reactive mode of coping with the crisis, the latter approach inevitably leads to denial, avoidance, and eventually stress. The proactive manager, on the other hand, seeks assistance in problem-solving, which reduces the likelihood of stress (Broussine and Guerrier 1983).

TABLE 2

Features Common to Middle Managers

- Accountable to someone above them in organization
- Rarely have authority to formulate policy
- May play a role in formulating policy
- Accountable for implementing policy
- Accountable link between those who achieve policy (employees) and those who formulate it (management).

From: Broussine and Guerrier, 1983

Nonetheless, crisis managers will be confronted with uncertainty as the problem persists or escalates (Andriole 1985). As a consequence, conflict may develop between the manager/employer and the occupant/employee because of the disparity between expectations and actual events. This conflict may have constructive or destructive effects, depending upon how it is handled (Kreitner 1979). Should the manager attempt to deny or avoid it, the situation inevitably will worsen; it will improve if the conflict is confronted directly and the focus is kept on issues rather than personalities (Leavitt et al. 1973).

Accordingly, in order to resolve conflict resulting from an IAQ problem, the manager must identify the problem early and develop alternative solutions. This may be easier said than done because the first inkling that an IAQ problem may exist is an increased number of employee complaints, which usually are non-specific (e.g., malaise, burning of the eyes, upper respiratory problems). In and of themselves, these symptoms may suggest but do not necessarily confirm that SBS exists. The implications obviously would be different for an office building than for a medical or research laboratory building. In the latter, for example, the complaints may result from poor laboratory procedures (e.g., improper or inconsistent use of a fume hood when handling volatile organic compounds).

When confronted with an IAQ problem, a manager not only may not be able to identify it as a crisis situation but also may not know where to turn for competent assistance. Managers often are required to turn to in-house experts who also may not totally understand the causes or required corrections for SBS or BAI. Should outside consultations be required, there obviously would be further delay in identifying the crisis or developing alternative solutions. Those delays and the coincident pressure for speedy action from the occupant/employee elevate the level of frustration experienced by the manager. Further, the conflict, uncertainty, and vagueness surrounding the crisis often result in anxiety and the need for more control by the manager (Meyers and Holusha 1986).

To some extent, the awareness of whether crises are managed successfully depends upon the viewpoint of the observer. The perception of the manager/employer may be quite different from that of the occupant/employee and, because perception is tantamount to reality, perceived "foot-dragging" or mismanagement may cause increased frustration and anxiety and decreased performance of the employees (Fink 1986). For conflict resolution to be successful, it is essential that occupants/employees and managers/employers work together and cooperate toward common goals or purposes and not be adversarial (Gold 1986).

That is, in dealing with crises, the manager must interact effectively with both subordinates and higher authority. In so doing, the manager must be able to maintain a successful balance between sensitivity to the needs and concerns of the occupants/employees and credibility with higher authority regarding the crisis. Further, to be effective, the manager must

be able to accept crisis as a normal, but unpleasant, occurrence (Meyers and Holusha 1986) and the notion that "stop-gap" measures, although expensive, usually are necessary during the resolution of the crisis. Equally important is the fact that those issues must be clearly communicated to all constituencies.

IMPORTANCE OF OPEN COMMUNICATIONS

Because people rely upon the media for information for decision-making, explaining what is going on, or adding structure to a situation, it is essential that uncertainty be minimized by opening and maintaining clear, regular, and open communications with all constituencies (i.e., employees, higher authority, public). This, at the minimum, involves regular meetings and timely updates. Inability to provide timely reports often results in rumors, which may not only give the wrong impression of the situation, but also interfere with resolution of the problem (Koenig 1985).

Media representatives often complain that management is not completely truthful regarding events, provide either delayed or no responses to inquiries, talk to the press only in good times, or provide distorted (i.e., usually favoring the organization) information. Administrators, on the other hand, complain that coverage is shallow, superficial, sensational, or deliberately destructive. Obviously, the best way to mitigate these differences is to provide effective communications with constituencies. This requires that the manager be aware of the concern of and develop an ongoing dialogue with others, think politically, and overcome natural aloofness and protectiveness.

Organizations must recognize that the public is interested in their problems and select spokespeople who are knowledgeable of the problem and who will be precise, factual, and unbiased in their presentations (Pinsdorf 1987). In some states, agencies are required to conduct all public business in the "sunshine." In those instances, administrators are faced with managing crises, including solving IAQ problems, in a veritable "fishbowl" where every action (and inaction) is subject to immediate scrutiny (and second guessing). Further, when dealing with an issue such as SBS, which is characterized by vague and nonspecific symptoms and varied causes, it is particularly difficult to communicate the impression that progress is being made in problem resolution. Nonetheless, in those situations where operating in the "sunshine" is a statutory requirement, administrators should consider this as an important advantage in communicating with all levels (i.e., employees, higher authority, the public).

Decision-making requires hard information and appearances—whether accurate or misleading—can be decisive regarding the outcomes (Pinsdorf 1987). An administrator/manager who continually strives to prevent an increase in or reduce frustration in employees will promote improved performance and interactions between employer/employee relations. Conversely, any delay in identifying and solving IAQ problems may cause employee frustration, which inevitably will lead to anger and may decrease productivity, but increase turnover, absenteeism, tardiness, and accidents. One of the main attributes a manager must possess is an ability to communicate well with others and motivate them to achieve goals (Dyer 1978).

CONCLUSIONS AND RECOMMENDATIONS

Because some organizations appear to be more crisis-prone than others, it has been recommended that a crisis capability audit be performed, preferably by an outsider. That audit is designed to provide information regarding how well an agency can detect, manage, and benefit from a crisis. The result is an institutional approach to potential problems that follows a predetermined plan (Meyers and Holusha 1986).

Irrespective of whether a crisis capability audit has been performed, when crisis warnings are detected it is essential that intervention be instituted as soon as possible (Fink 1986). Perhaps the most important factor is the naming of a manager who will be the main source of information and instructions. This individual must be sensitive to and understand early warning signals and pinpoint the problem (Slatter 1984) as well as work for consensus, develop an action plan, and initiate remedial actions (Andriole 1985).

Some managers find it difficult to deal with public agencies because crises that affect the public often bring increased scrutiny (Meyers and Holusha 1986). Nonetheless, it is imperative that contacts be made with all constituencies. This requires that an articulate media spokesperson who is thoroughly familiar with the problem be appointed as soon as practicable (Pinsdorf 1987). All relevant information describing the problem should be made available to the employees/occupants and the public and updated on a regular basis.

Above all, the problem should be remedied as soon as possible because delay may damage the organization's reputation (Meyers and Holusha 1986) and possibly the manager's health. By exercising control and a proactive approach, the manager will significantly decrease the potential for stress and increase the likelihood that goals are achieved (Broussine and Guerrier 1983).

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DISCUSSION

James V. Dirkes II, University of Michigan, Ann Arbor, MI: Even though I agree that good communication and prompt response are desirable, it seems that indoor air quality issues often don't have clear causes. Thus they don't have clear solutions which can be acted on with a high degree of confidence. Please comment on this.

E.L. Besch, College of Veterinary Medicine, University of Florida, Gainesville, FL: Your comments grasp the essence of my presentation. I agree that IAQ problems often have unclear causes and unclear solutions and, as a consequence, may constitute crises (i.e., they are turning points for better or worse or, in other words, they are situations that have reached a critical phase) and should be managed as such. IAQ problem management is difficult because of the need for instant expertise in matters that are not well understood. Strategies to correct the problem are often stopgap, expensive, and unsuccessful. Nonetheless, they should be implemented as soon as possible and communicated to all concerned to prevent the perception that managers are not responding to the concerns of the occupants/employees. Further, crises that are unmanaged or perceived to be unmanaged result in consequences on building occupants/employees (e.g., non-performance, denial, anger, frustration) that are equally important but separate from those relating to the IAQ problem per se (e.g., eye irritation, upper respiratory problems, headache, lethargy).

Ventilation and Pressurization

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DETERMINING DELIVERED QUANTITIES OF OUTSIDE AIR: CO_2 TRACER GAS, OR BOTH?

William A. Turner, P.E. **David W. Bearg, P.E.**

INTRODUCTION

As part of an indoor air quality investigation protocol, a major focus is frequently a determination of the quantities of outside air (OA) actually being delivered to the occupants of a building. This quantity of OA being delivered to the occupants is a function of both the quantity of OA taken in at the OA dampers and the effectiveness of the HVAC system in delivering this air to the people. In this paper, *the ratio of the air quantity entering the OA dampers and the outside air quantity delivered to the occupants is referred to as the ventilation efficiency (others have suggested this be called ventilation performance).* Often, it is desirable to know this ventilation efficiency in order to determine if improvements in the delivery efficiency are warranted. Measurement of both the delivered quantities of outside air and the efficiency of the ventilation system is especially important in light of various protocols for design options, which are contained in proposed ASHRAE Standard 62-1981R, "Ventilation for Acceptable Indoor Air Quality."

The two principal tools currently utilized for evaluating the quantity of outdoor air (OA) delivered to the occupants of a building are the measurement of carbon dioxide (CO_2) concentrations and the measurement of tracer decay rates using sulfur hexafluoride. These two methods have also been utilized by the authors and other researchers to assess the efficiency of outside air delivery. Each of these techniques has its own set of advantages and disadvantages, but the performance of the two together tends to cancel out some of the weaknesses of each. Therefore, whenever possible, the authors have performed both procedures side by side to maximize the precision and the accuracy of the results. This paper discusses some of the issues raised by the results that have been obtained and presents suggestions for minimizing errors in the interpretation of the test results.

INFORMATION THAT CAN BE DERIVED FROM CARBON DIOXIDE TESTING

CFM Outside Air Per Person

A ventilation rate determination using CO_2 measurements compares the indoor concentrations with outdoor concentrations and assumes that the increase in indoor values is due to the buildup of CO_2 expired due to respiration by the building occupants. This relationship is detailed in Appendix D of ASHRAE Standard 62-1981 (ASHRAE 1981). An advantage of this technique is that relatively few measurements, obtained during the typical peak late-morning or mid-afternoon occupancy period, can provide a determination of the quantity of ventilation air being provided at the time of measurement. The results express the ventilation rate in terms of cubic feet per minute of outdoor air per person (cfm of OA per person), which is then directly comparable with the recommended minimum OA quantities published in ASHRAE Standards 62-1981 and 1981R (ASHRAE 1981, 1986), which are currently being adopted or considered by states such as Maine and New Jersey (State of Maine 1988; State of New Jersey 1988).

Ventilation Efficiency (Performance)

Although the determination of cfm of OA delivered per person is very useful, it is not sufficient for the scope of many evaluations. For instance, in order to compare the quantity of OA delivered with the quantity of OA that is measured to be entering the OA intake of the HVAC system, the delivered quantities need to be expressed in terms of just cfm of OA. The cfm of OA at the air intake is often determined by flow measurements, while the delivered quantity is the product of the CO_2-derived cfm/person value and the total number of people present at the time of the test measurements. Thus, in actual testing situations, it is necessary to know exactly how many people are present in the space at the time of the CO_2 measurements to convert the results from cfm/person values to cfm values. For small buildings with populations up to 30 or so people, this rarely presents a problem, but for large buildings with 300 people or so, the ability to count the number of people is much more difficult. Techniques for estimating this population are, of course, possible. As part of building surveys, we have measured not only CO_2 concentrations, but potential number of people per office and actual number of people per office. Then, assuming that the 20% of the "random" offices surveyed are typical of the rest of the building, we can estimate the total building population. This then yields the OA quantity in terms of cfm.

CFM Outside Air Per Square Foot

Dividing cfm of OA value by the area involved yields another important evaluation criterion, cfm of OA per ft^2. Corporate and lease ventilation standards are often expressed in terms of minimum quantities of cfm of OA per ft^2. This contrasts with ventilation standards, which have assumed human beings to be the principal or exclusive polluters in offices and similar spaces. This type of cfm/ft^2 approach has recently been presented as an important criterion by Fanger (1988).

For typical office environments (as defined by ASHRAE 62-1981R), with seven people per 1000 ft^2 area, the proposed ASHRAE minimum ventilation rate value of 20 cfm of OA per person is equivalent to 0.14 cfm of OA per ft^2 of office space. This outdoor air delivery rate can be contrasted with total air delivery rates for ventilation and air conditioning, which are typically around 1.0 to 1.2 cfm per ft^2 of office space.

Building Volume Air Changes Per Hour of Outside Air

In addition to expressing the ventilation rate in terms of cfm of OA per person or per ft^2, the ventilation rate can also be expressed as the number of air changes per hour (ach). In the authors' opinion, it is this expression of the ventilation rate that most accurately represents the rate at which air contaminants generated within the building envelope are diluted and removed from the space. This is also the format for the results from tracer decay ventilation testing.

For the ASHRAE-defined typical office, with 20 cfm/person, seven people per 1000 ft^2 and total ceiling heights of

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about 10 ft, the outdoor air ventilation rate would be 1.0 ach. Factored into this calculation is the empirical result, from the authors' experiences with tracer gas studies, that the net effective volume can be estimated as being 85% of the gross volume of the space.

POSSIBLE INTERPRETATION DISCREPANCY (CO_2 MEASUREMENTS)

These distinctions in expressing ventilation rates in units of cfm OA/person, cfm OA/ft², and ach OA become especially important in *atypical* office-type spaces, which are often found in a variety of office building types. For example, in one evaluation of a complaint building, with total ceiling heights of 18 ft, utilizing the CO_2 approach, data were collected which yielded a peak average indoor concentration of 713 ppm with 425 ppm outdoor conditions, yielding a ventilation rate of 36.5 cfm of OA per person. For the measured population estimate of 300 people, this represented 10,950 cfm of OA. Tracer gas testing conducted at the same time yielded a value of 0.65 ach. When this ach was applied to the area of 60,000 ft² and an estimated effective volume of 972,000 ft³, it yielded 10,530 cfm of OA. Both of these values (in cfm) are very similar and can be expressed as 0.18 cfm of OA per ft². The question remains, however, as to which criterion is the one to use in recommending a ventilation rate sufficient to prevent complaints of inadequate ventilation. In this situation, it is the ventilation rate expressed in terms of ach that is most directly concerned with the rate at which air contaminants such as environmental tobacco smoke (ETS) or other internally generated pollutants are diluted and removed from this space by OA.

The determination of the most appropriate ventilation goal and the criteria of meeting that goal, i.e., cfm/person, cfm/ft², or ach, can have a profound effect on the age of the air within the building, resulting air quality in the space, and the amount of outside air needed to provide acceptable air quality. Further research is needed related to the most appropriate evaluation criteria for the delivery of outside air to the breathing zone, or occupied zone, and the appropriate terminology for specifying the ventilation rate.

CARBON DIOXIDE MEASUREMENT AS A DIAGNOSTIC TOOL

Limitations of Carbon Dioxide Testing Alone

Measurements of CO_2 concentrations at different indoor locations can point out localized variations in ventilation rates throughout a building. Measurements comparing the concentrations in the supply ductwork and the return ductwork as well as the occupied spaces can characterize the ratio of outdoor air to recirculated air leaving the HVAC equipment. Measurements obtained in the early morning can document the persistence of air contaminants from the evening before where the building occupancy extends beyond the operation of the ventilation system. Early morning measurements can also assess the impact of air contaminants from parking garages.

The measurement of CO_2 concentrations has also been used by the authors to detect the presence of inadequately vented combustion appliances, i.e., a poorly vented gas-fired hot water heater affecting a university classroom building. The interference of CO_2 from sources other than the occupants, such as the unaccounted-for presence of the products of combustion, can lead to very erroneous ventilation rates. This was reported in the case of an investigation of a warehouse/showroom that was heated with direct-fired gas heaters.

Therefore, in order to trust the results from a CO_2 analysis, one must be certain that there are no products of combustion entering the building or mechanical systems. A potentially limiting aspect of the CO_2 approach is the precision of the sampling technique used. CO_2 detector tubes have a relative standard deviation of 10% and detectors based on CO_2 absorbance in the infrared band typically display their results to only the nearest 50 ppm. A display reading of 850 ppm could therefore actually be 826 ppm or 874 ppm. Taking into consideration the combined uncertainties of detector results and the number of people present in the building typically leads to cfm of OA results being stated as a range of values with expected upper and lower bounds.

Another disadvantage of this approach is the requirement for a sufficient density of people, within a small enough volume, in order to obtain a measurable increase in indoor concentrations as compared with outdoor concentrations. The extreme example of this is when we have been called upon to evaluate a building that has been evacuated and is devoid of the products of human respiration. This situation then requires the use of tracer testing for a ventilation rate evaluation.

VENTILATION INFORMATION THAT CAN BE DERIVED FROM TRACER TESTING

Building Volume Air Changes Per Hour of Outside Air

As already mentioned, the tracer decay testing approach yields its results in terms of ach. This approach is based on measuring the rate of decrease of a tracer, such as sulfur hexafluoride, that has been uniformly dispersed throughout the space under investigation. If the space under investigation is behaving as a single, well-mixed chamber, the measurements will yield a straight line on a semi-log plot (ASTM 1983). The slope of this plotted line is equivalent to the ventilation rate and can be expressed in terms of ach. Calculations are based on the relative changes in tracer concentration and do not require an absolute calibration of the analysis equipment. (See Figures 1 and 2 for typical tracer plots.) As with the CO_2 assessment approach, the quantity of OA often needs to be expressed in terms of just cfm of OA in order to evaluate the performance of the HVAC system. To convert tracer-determined ventilation rates (expressed in terms of ach) to cfm values, it is necessary to multiply the ach values by the volume into which the tracer has been disbursed. This tracer mixing volume, or effective volume, will be somewhat less than the gross physical volume of the structure due to the presence of furnishings, equipment, and stagnant zones either in corners of the occupied space or due to a large return air plenum above a suspended ceiling. This volume can be determined from procedures that require a very precise determination of the rate of tracer release and the absolute quantity of the tracer measured (ASHRAE 1985). In the authors' experience, typical conventionally designed office spaces are in fact well mixed, with typically 85% of the air being recirculated during the air-conditioning or heating mode. The assumption of a clearly defined single zone, however, varies from case to case. The potential uncertainty as to the volume for the dispersal of the tracer leads to results being stated as a range of values with expected upper and lower bounds. The actual shape of the tracer decay plot is an additional source of both useful information to characterize

the behavior of the ventilation system and uncertainty as to the ventilation rate. Slopes that deviate from linearity (on a semi-log plot) indicate variations from the well-mixed case; slopes with the appearance of an increasing slope with time are representative of displacement or plug flow, while slopes with the appearance of a decreasing slope with time are representative of incomplete mixing and zones of stagnation. It is only when the plotted slope is linear that the ventilation rate can be determined with absolute certainty.

Most building investigations do not have the budgets to support the precise determination of the effective volume of the tracer dilution; thus, an estimate based on the gross volume is more typically used. Our experience indicates that estimates of effective volume that are 85% of the gross volume yield reasonable results. This is an area in which more research would be very useful.

POSSIBLE INTERPRETATION DISCREPANCY (TRACER GAS MEASUREMENTS)

Overestimation of ACH (Between Zone Mixing)

Cross-contamination between different zones of a complicated HVAC system can lead to erroneous results, i.e., in one example, one part of the building was being impacted by air contaminants being generated in another part of the building. The airflow relationship was such that the air being delivered to the space being evaluated had already traveled through another occupied part of the building. Tracer decay testing performed only in this space of interest failed to take this into consideration and initially yielded an outside air ventilation rate much higher than was actually being provided. Multiple tracer gas tests with releases occurring in different HVAC zones and transport evaluation being conducted or the use of CO_2 testing (with a sufficient density of people) were required to yield accurate representative results. In this particular situation, the evaluation included several locations within a building complex. The complex consisted of two adjacent buildings that had been interconnected. The direct release of the tracer into the occupied area of the smaller of the two original buildings, with 4100 ft² per floor (the adjoining building has 16,500 ft² per floor), yielded a linear decay rate equivalent to 4.3 ach. For the estimated volume of this space, this represented 2320 cfm of OA. The CO_2 test results, however, based on 700 ppm indoors and 400 ppm outdoors with 17 people present in the space, yielded a ventilation rate of 35 cfm per person or a total of 595 cfm of OA. An additional tracer test of the same study area, but with the tracer being released into the HVAC system located in the larger building three floors above, yielded a tracer decay rate equivalent to 1.1 ach. This 4100 ft² area had a total ceiling height of 9.3 ft, leading to a gross volume of 38,100 ft³. Using the previously mentioned relationship of the effective volume for occupied office spaces being 85% of the gross volume, the net volume is 32,400 ft³ and the 1.1 ach yields an effective ventilation rate of 594 cfm of OA, which is the same result as that from the CO_2 calculation.

This example also points out that with both assessment approaches, it is crucial to be familiar with the design of the HVAC system as well as the intended modes of operation and the need to be aware of any changes in the operation of the system which could affect the quantity of OA being delivered throughout the testing period.

COMPARATIVE ADVANTAGES AND DISADVANTAGES OF EACH APPROACH

In using the carbon dioxide measurement approach, the accuracy of the result is limited by the precision of both the CO_2 measurement device and the counting of the number of people actually present in the building during the CO_2 measurements. In using the tracer decay approach, the accuracy of the result is limited by the accuracy of the estimate of the effective volume of the space under investigation and the linearity of the semi-log plot of the tracer decay values. In both of these approaches, the results are typically presented as being between a given upper and lower bound. The performance of both of these assessments together can reduce these bounds.

The authors have been known to say that "most buildings are similar but each building is unique." Some of these unique situations point out the strengths and weaknesses of these two investigatory approaches. For example, the results from one unusual office building, with a height of 18 ft from floor to roof deck, where both procedures were used, are presented in Table 1.

In this table, the range of values for the tracer testing results reflects estimates of the effective volume ranging from 80% to 95% of the gross volume. The range for the CO_2 results reflects the ±25 ppm aspect of the detector device. In this table, each test refers to a different zone of the building, with the exception of Tests 6 and 7, which are for the

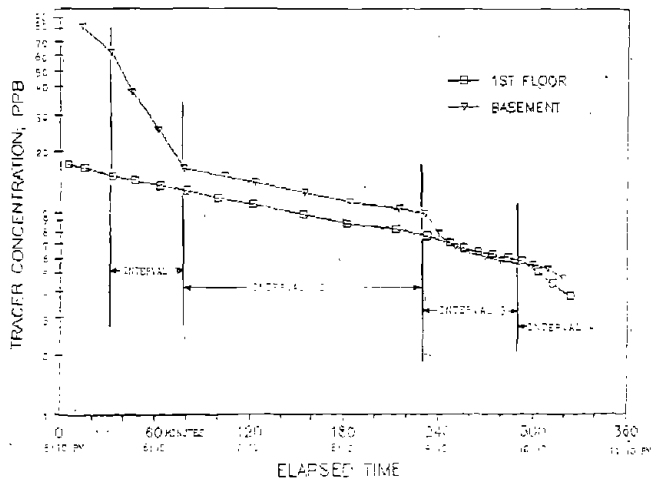

Figure 1 Tracer concentration vs. time

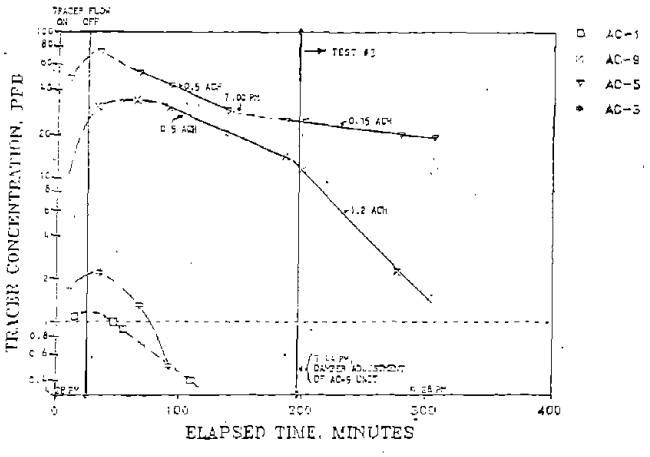

Figure 2 Tests 2 and 3

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TABLE 1

Comparison of Outdoor Air Quantities from Tracer Testing and CO_2 Testing

Test Zone	CFM from Tracer Decay	CFM from CO_2 Test	CFM from Combination
1	9340–11100	10,100–12,000	10,100–11,100
2	3060– 3630	1900– 3800	3060– 3630
3	1770– 2100	630– 840	?
4	1000– 1700	1470– 1960	1470– 1700
5	250– 1100	700– 1050	700– 1050
6	820– 960	980– 1180	970
7	1730– 2050	1960– 2940	1960– 2050

same zone, but with the OA dampers in different positions. In five of these seven examples, the combination of the results from the two evaluation techniques reduces the uncertainty of the determined cfm of OA quantites. In one example, the range for the tracer results fell entirely within the range of results from the CO_2 evaluation. In test zone 3, however, the ranges of expected results did not overlap. This space, in addition to being a candidate for testing, was a laboratory space, with fume hood exhausts and a low population density. Another confounding aspect of this space was the presence of a lot of equipment, which would be expected to reduce the effective volume. This provides an explanation as to why the tracer results exceed the CO_2 results.

VENTILATION EFFICIENCY EVALUATIONS (VENTILATION PERFORMANCE)

One reason the OA quantities presented in Table 1 were expressed as cfm values and not as ach or cfm/person values is that they were to be compared with the amount of OA determined to be entering the HVAC system. There needs to be greater recognition of the fact that measurement of the quantity of OA measured as entering the air intakes of an HVAC system does not necessarily reflect the quantity of OA delivered to the building occupants. In the authors' experience, diffuser sizing and appropriate supply and return location is very important in order to minimize complaints of drafts and noise and to promote good mixing. With supply and return systems of conventional design (both in the ceiling), good mixing is important in order to minimize inefficiencies in the HVAC distribution system and the poor operational economics caused by the short-circuiting of supply and return airstreams. Rather large inefficiencies of outside air and cooling air distribution have been observed in several conventional-type office/research buildings evaluated by the authors. These data are presented in Table 2.

In this data set, the evaluation of the OA quantity entering the HVAC system at the air intakes was either determined by direct measurement of the air volume or by combination of the measurement of total flow at each air-handling unit plus an apportionment by enthalpy balance to determine the percentage of the total flow consisting of outdoor air. The evaluation of the "delivered" OA quantity was determined from measurements of carbon dioxide in the occupied spaces in combination with population counts as an assessment of the number of people present in the building at the time of these CO_2 measurements. These CO_2 concentrations yield a value for effective ventilation rates expressed in terms of cfm/person. Since it is the number of people actually present that is the source of the CO_2, the actual number of people present in the building needs to be determined to convert this ventilation rate into a quantity that can be expressed in units of cubic feet of OA per minute (cfm).

TABLE 2

Comparison of Range of Measured Outdoor Air Volumes into the HVAC System and Delivered to Building Occupants

Test Location	%OA	Measured OA, CFM Into System	CO_2-Determined CFM to People	Ventilation Performance
A	50	90,600	12,600–17,400	14–19%
B	44–67	50,000–80,000	20,200–25,750	40–52%
C	40(avg)	38,000–38,500	9150–11,400	24–30%
D	30–60	38,200	12,200–15,200	32–40%
E	28	31,000	7200–12,000	23–39%
F	19	18,700	7000–14,750	37–79%
G	15	18,000	9900–13,800	55–77%

NOTE: Each test location represents approximately 125,000 ft^2 of space.

Since the absolute number of people in the building was not determined with certainty, a range of expected minimum and maximum values is used to bracket the expected result. The lower bound was determined from a count of people present vs. the desks per office as part of the building survey. This ratio of percent of people present was then applied to the total reported population. In case the census undercounted the actual number of people, the upper bound for this range assumed that 80% of the potential number of people were present even if fewer were counted. In this data set, the range of people present varied widely, from population counts below 40% up to 80%. This cfm/person term is therefore multiplied by the range of the number of people present at the time of the building survey to yield values of the absolute quantity of OA, expressed in cfm.

Limited information available on other buildings, outside of this particular study, suggests that losses of 25% of this OA can normally be expected. Distribution inefficiencies are important both from an economy of operation perspective as well as because they interfere with the delivery of OA to the building as a block from actually getting to where the people are. Typical causes of distribution inefficiencies are:

1) leakage from the supply air ductwork directly to the return air plenum,
2) poor mixing due to short-circuiting of low-velocity discharges across the ceiling and back to the return plenum without penetrating to the occupied zone, and
3) the delivery of OA to unoccupied areas in the building.

With respect to this last item, for instance, for the building data presented in Table 2, the total area occupied by people typically represented only 60% of the gross areas of the building. The extent that a portion of the outdoor air delivered to the building is going to unoccupied areas would explain a portion of the difference between the OA quantities measured to be entering the building as compared with being delivered to the building occupants' offices.

Other contributing factors might be that there are imbalances of makeup air between adjoining buildings, which may also account for a decrease in the delivery efficiency. In a building that is not operated under slight positive pressure, uncontrolled infiltration into the building shell could increase the OA for ventilation without increasing the quantity measured at the OA dampers.

INFILTRATION

The issue of infiltration is of special interest because the determination of the quantity of OA delivered to the building occupants, either by the CO_2 or tracer technique, does not

differentiate between OA delivered by the mechanical ventilation system and that entering the building due to infiltration through the building shell. Assessing the magnitude of the infiltration component is achieved in combination with other aspects of the building evaluation. Infiltration, if it is occurring, is dependent on two conditions: the presence of leakage sites in the building shell and the existence of areas in the building that are at negative pressure with respect to the outdoors. While it can be expected that there will always be some leakage sites, the building typically should be operating at a slight (0.05 of water column) positive pressure with respect to the outdoors. The identification of leakage sites is achieved by the use of air current tubes, which provide a visual indication of local air movement. Once a leakage site is detected, the direction of air movement will indicate the pressure relationship at that location. This, in turn, indicates whether infiltration is occurring or if the building is being maintained at a positive pressure with respect to the outdoors as it should be. Since infiltrating air does not receive the benefit of filtration, a clue that infiltration is occurring is the presence of dust on surfaces, especially on VDT screens. This assumes that the ductwork is clean and that there are adequate filters in place.

Quantification of the amount of infiltration entering the building, if it is significant, can be determined by subtracting the OA quantity measured as entering the HVAC system from the amount of OA determined to be delivered to the building occupants. Another approach is to perform a tracer evaluation with the OA dampers closed. The ventilation rate occurring under this condition will be primarily due to infiltration. There may, however, be some leakage past the OA dampers.

From an economics of operation standpoint, good delivery efficiencies should be pursued. Reducing these inefficiencies would allow many buildings to more often meet ASHRAE outside air guidelines over a greater range of operating conditions, allowing this to be accomplished with significantly less outside air being brought into the HVAC system, and with less total air movement required. An expected side benefit is an increased ability to deliver more of the installed cooling capacity to the occupied spaces.

CONCLUSIONS

We have presented information that can be derived from the measurement of the amount of outside air delivered to the occupants and discussed many of the pitfalls evaluators should be cautious of. Done correctly, a ventilation assessment can point out whether or not there is a need for improvement in a ventilation system. Performed without a clear understanding of the limitations of the methods, the HVAC system, and the needs of the occupancy of the building, the results can lead to a serious misinterpretation of what is actually happening within a building system.

ACKNOWLEDGMENTS

The authors wish to thank all of our clients who have so willingly cooperated in our building investigations and allowed our findings to be utlilized for educational purposes. We would also like to thank the support staff of Harriman Associates for the preparation of this manuscript.

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DISCUSSION

Carl N. Lawson, LRW Engineers, Tampa, FL: Were any of your tests conducted in the breathing zones of the areas of concern? Do you feel the supply air distribution gives the best results in determining the outdoor air quantities? Why?

W.A. Turner, Harriman Associates, Auburn, ME: All tests were conducted in the breathing zone of the occupants, i.e., typically 4 to 6 ft off the floor. Testing is also conducted at supply diffusers and return grilles. No, supply air only tells you what is entering the occupied space, if the air turnover rate is low, or if occupancy is high. It will seldom be representative of the breathing zone of the occupants.

John A. Tiffany, UMDNJ-RWJ Medical School; NIOSH Educational Resource Center, Piscataway, NJ: Do you ever suggest using grab samples for CO_2 measurement (due to its inaccuracy and no long-term measurement factor)?

Turner: I do not use short-term grab samples to make economic or health decisions for a client. Measurements must be well understood in conjunction with an understanding of what the HVAC system is or is not doing. The investigator must understand how the changes in the ventilation system operation would be expected to affect the measurements.

P.E. McNall, Phoenix Engineers, Overland Park, KS: What are the specifics of how to measure in the breathing zone? Where is it done and for how long?

Turner: When we measure in the breathing zone, we attempt to measure between approximately 4 ft and 6 ft off the floor. With a CO_2 instrument, we would measure until a stable reading is reached, typically 2 to 3 minutes. With an SF_6 sample, we would collect the sample over a 30-second time period, typically. In both cases, we try not to disturb the normal activities of the occupants.

INVESTIGATION OF THE INDOOR AIR QUALITY, AIRTIGHTNESS, AND AIR INFILTRATION RATES OF A RANDOM SAMPLE OF 78 HOUSES IN WINNIPEG

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G.M. Comeau, P.E.

ABSTRACT

An investigation of the indoor air quality, airtightness, and air infiltration rates of 78 randomly selected houses in Winnipeg was conducted in the summer of 1987. Physical characteristics of each house were also recorded along with information on occupant behavior and attitude toward indoor air quality. Approximately 750 observations were made on each house.

The objective of the project was to obtain results that were representative of the Winnipeg housing stock. Therefore, a three-level sampling procedure was adopted, and every effort was made in gaining access to the houses selected by this procedure.

Indoor air quality was determined by measuring the pollutant levels at three locations in the home. The pollutants measured were carbon dioxide, carbon monoxide, formaldehyde, radon, ozone, and respirable suspended particulates. Airtightness was measured by the fan depressurization method; air infiltration was measured using the grab sample, tracer gas decay technique.

Indoor air quality was related to usage of exhaust fans in the home. Each fan was described in detail, recording its frequency of use, and measuring its sound pressure level.

INTRODUCTION

In recent years it has been realized that our greatest exposure to pollution is not outdoors, but in our homes and workplaces, where we spend the majority of our time. However, the magnitude of the problem has not yet been clearly defined. We do not know the health effects of most pollutants with certainty, nor do we know their concentration distributions. The purpose of this study was to learn more about the latter.

Among the factors that influence pollutant concentration in a house are its location and its physical characteristics including age, style, volume, envelope area, and detailed information about the heating, ventilating, and air-conditioning equipment. To study the influence of all these parameters will require that a large variety of houses be studied. Using a large enough random sample of housing should provide this variety and also provide results that are representative of the housing stock in the region sampled. Of course, in obtaining a sample of this nature, self-selection should be avoided since homeowners who are concerned about their indoor air quality or have noticeable indoor air quality problems would be the first to participate.

While the physical characteristics of the home may affect the indoor air quality, occupant behavior is also an important factor. For example, ventilation fans can help to maintain indoor air quality, but are frequently not used because homeowners object to the noise. Other examples of practices that may affect indoor air quality are the frequency with which windows are opened and closed, and hobbies such as wine making, painting, and ceramics.

This paper summarizes the results from an indoor air quality study of 78 randomly selected houses in Winnipeg. Indoor air quality, which was determined by directly measuring the various pollutant levels, was related to airtightness, air exchange rate, and occupant behavior. Noise levels of exhaust fans were measured and related to their frequency of use.

HOUSE SELECTION AND LEVEL OF RESPONSE

The objective of the house selection procedure was to ensure that the houses studied were representative of the Winnipeg housing stock. A three-level sampling procedure was used. First, 13 census tracts were selected at random from the 127 census tracts in the city of Winnipeg. Then a list of all the streets in each census tract was made, and three streets were selected at random. From each street, two houses were then selected at random.

To eliminate bias from a sample of households, it is necessary to eliminate self-selection. The selection technique used in the present study would eliminate self-selection if all householders selected by the random sampling technique agreed to participate. Every effort was made to come as close as possible to the objective of gaining access to houses selected by the random sampling technique.

A considerable amount of time was spent soliciting homeowners of the houses selected. To keep this time to a minimum, houses with no occupants at home when called upon were excluded from the study, provided that all calls were made in the evening. This time was chosen so that there would be no bias toward families where adult members are not at home during the day. When a call was made on a selected house and no one was home, it was replaced with the one next door having a higher street number than the one originally selected. While this procedure may have influenced the objective of random sampling, it was consistent throughout the entire study and always resulted in the selection of houses similar in age and appearance to the ones originally selected at random.

Every effort was made to ensure that the householders who were at home when called upon would agree to participate in the study. This was done by preparing a preliminary letter that was sent out to each householder before he/she was called on, arranging media publicity about the survey, arranging for the local Conservation and Renewable Energy Office of Energy, Mines and Resources Canada to act as a reference for the legitimacy of the project, and choosing personable and aggressive people to make the call on the householders.

This approach resulted in an overall acceptance rate of 56% (percentage of affirmative responses from houses originally selected). Close to 100% acceptance was frequently achieved in the higher-income census tracts, while on one

street in a low-income area, the acceptance rate fell to about 4%. About one-third of these householders would not even answer their doors, and the majority of the rest simply slammed the door as soon as they realized the caller was not someone known to them. Thus, there was no possibility of achieving a high acceptance rate on this street or on some others where attitudes were similar.

Figure 1 shows the fraction of houses which were either the original house selected or the first house where occupants were home, starting from the originally selected house, to which access was gained. Figure 2 shows the overall success rate for each district. The response level is the number of houses tested divided by the number of houses contacted. Houses where occupants were not at home were not considered as negative responses.

To substantiate whether or not the selected houses were representative of the houses in each census district, Statistics Canada data on house age, number of occupants, and number of rooms were obtained. As would be expected in a randomly selected sample, the average age, number of rooms, and number of occupants for the houses of each census district was generally similar to the corresponding Statistics Canada data. The average age of all houses studied was 42 years; the average age of housing in the 13 census tracts based on Statistics Canada data was 41 years. Similarly, the average number of rooms in the houses studied was 6.9 as compared with 6.2 from the Statistics Canada data. The average number of occupants in the homes studied was 3.0; based on Statistics Canada data, the average number of occupants was 2.9.

TEST METHODOLOGY

Indoor air quality, air infiltration, airtightness, and exhaust fan noise level measurements were made in each house. Also, homeowner survey and technical survey report forms were completed to physically describe the house and to determine other information such as homeowner attitude toward indoor air quality, number of occupants, time that each occupant spends in the home, and practices within or outside the home that may affect the indoor air quality. The total time required to test each house was approximately 3.5 hours, and involved two visits. This amount of time was tolerated by most homeowners and was sufficient for gathering all of the relevant data.

Pollutant measurements were made to substantiate the indoor air quality in each house. Included in these measurements were carbon dioxide, carbon monoxide, radon, formaldehyde, respirable suspended particulates, and ozone. Air infiltration was measured using the tracer gas decay technique. Airtightness was measured using the blower door depressurization method.

Air Quality Measurements

Carbon Dioxide. The carbon dioxide (CO_2) concentration was measured at three locations in each house with a portable CO_2 monitor. These measurements were made immediately after the survey team arrived at the house to be tested. Thus, the carbon dioxide concentrations were measured before the presence of the survey team had any effect on the results. Because visits were made at various times of the day, at the householders' convenience, the carbon dioxide measurements were not necessarily representative of the levels attained by just the presence of the house occupants at the times of measurement. In some cases, one or more occupants of the house left for work or school just before the arrival of the survey team.

Carbon Monoxide. Carbon monoxide (CO) concentrations were measured with a CO instrument. The device could only measure carbon monoxide levels to the nearest part per million (ppm). Since carbon monoxide levels are generally low in residential housing, measurements made with this device only indicated the presence of carbon monoxide, and not precise levels that are required for comparison purposes.

Radon. Radon levels in the surveyed houses were measured by two methods. Instantaneous measurements in working levels (measurement of radon progeny) were made at three locations in each house using membrane filtration. Radon was also measured by placing a week-long passive sampler in the basement.

The membrane filtration technique involved the drawing of 30 liters of air through a .8 mm membrane filter. A sampler operating at 3 liters per minute for 10 minutes was used to perform this task. Counts from the filters were measured in the scintillation cell of a radon detector. Measured count rate, counting efficiency, sample volume, and an appropriate Kusnetz factor (a function of the time between testing and analysis) were used in the calculation of working levels.

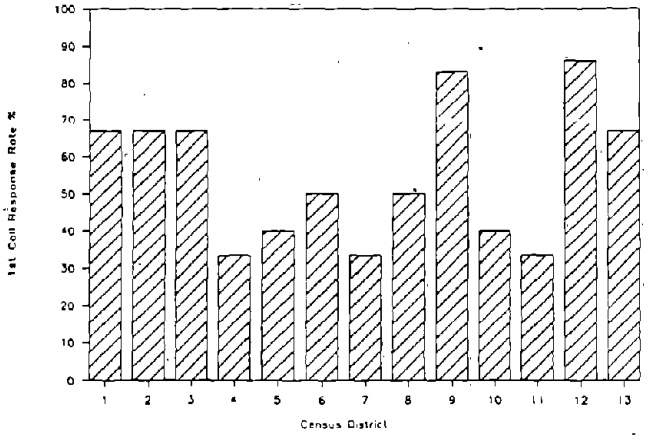

Figure 1 Percentage of houses that were either 1) the house originally selected or 2) the first house in which occupants were home starting from the originally selected house to which access was gained

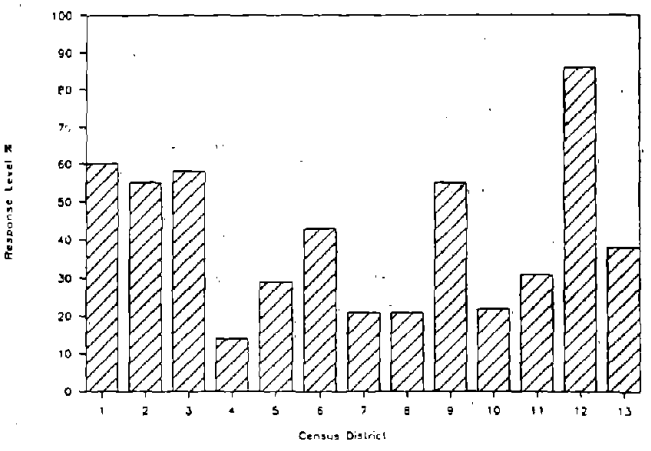

Figure 2 Average number of houses called upon per house to which access was gained

TABLE 1

Summary of Air Quality Measurements

	Average Concentration	Maximum	Minimum	Standard Deviation	Number of Measurements
Living Room					
CO (ppm)	0.7	4.0	0.0	1.0	76
CO_2 (ppm)	885	3100	350	431	76
RSP's (mg/m^3)	0.05	0.2	0.0	0.071	55
HCOH (ppm)	0.090	0.261	0.000	0.068	50
Rn (WL)	0.007	0.047	0.000	0.010	71
O_3 (ppb)	0.3	6.0	0.0	1.0	55
Basement					
CO (ppm)	0.7	4.0	0.0	0.9	69
CO_2 (ppm)	762	3000	330	374	68
HCOH (ppm)	0.088	0.235	0.000	0.064	45
Rn (WL)	0.012	0.062	0.000	0.014	71
Rn (pCi/L)	4.5	16.1	0.8	3.4	70
Bedroom					
CO (ppm)	0.4	3.0	0.0	0.7	73
CO_2 (ppm)	825	3000	290	430	70
HCOH (ppm)	0.092	0.285	0.000	0.073	49
Rn (WL)	0.007	0.049	0.000	0.010	59

Week-long radon measurements were made using the charcoal adsorption technique.

Formaldehyde. A formaldehyde monitoring kit was used for measuring the formaldehyde levels at three locations in each house. Passive bubblers were placed in each location for two hours and were subsequently analyzed by measuring the developed color in each sampler with a colorimeter. The color method used in this kit was the 3-methyl-2-benzothiazolone hydroazone hydrochloride (MBTH) method.

Respirable Suspended Particulates. Respirable suspended particulates (RSP) were measured at one location in each house with a respirable dust monitor. Because the instrument was designed for industrial applications, it could not give precise RSP measurements. However, the instrument was suitable for indicating high and low RSP levels.

Ozone. A multi-gas detector pump with long-range detector tubes was used to measure the ozone concentration at one location in each house. Each sample required 100 strokes of the detector pump and was too time-consuming to warrant measurements at two other locations (measurements were made in the living room on the main floor).

Relative Humidity. Relative humidity was measured using a sling psychrometer. Measurements were made on each floor of the house.

Airtightness and Air Infiltration Measurements

Airtightness. Airtightness was measured by the fan depressurization method. Testing was conducted according to the CGSB Standard, "Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method" (CAN/CGSB-149.10-M86) with the exception that intentional openings were not sealed. However, dampers on fireplaces were closed since they are normally closed when fireplaces are not utilized. While this practice increased the measured equivalent leakage area, it was consistent with the procedures carried out during the tracer gas tests.

Air Infiltration. One air infiltration measurement was made in each house using the tracer gas decay technique. In houses with forced-air heating systems, the tracer gas (sulphur hexaflouride) was injected into the return air plenum and samples were withdrawn from the same location. In houses with hydronic heating systems, the tracer gas was injected proportionately throughout the house, and samples were withdrawn from a central location. In either case, the mixing time was a half-hour.

Sound Level Measurements

A sound level meter (SLM) and an octave band filter set were used to perform the sound pressure level measurements. The SLM reference pressure was 2×10^{-5} Pa. Signals were processed by two different methods:

1. Weighting network, which corresponds to an inverted equal loudness contour at low pressure levels, and
2. Linear network, which enables the signal to pass through unmodified.

In addition to these measurements, a frequency analysis, which measures the sound levels at nine preferred frequencies, was also performed.

RESULTS FROM AIR QUALITY, AIRTIGHTNESS, AND AIR INFILTRATION TESTING

The random selection procedure resulted in a sample containing a wide variety of housing of which all were single detached dwellings. House construction dates ranged from 1902 to 1980, with the average house construction date being 1945. Of the 78 houses surveyed, 63 had forced-air heating systems, and 15 were heated hydronically. One of the houses that had forced-air heating had an electric furnace; the remainder used natural gas. Thirty-eight of the houses had central air-conditioning.

A summary that outlines the results from air quality measurements made in the 78 houses is contained in Table 1. Average levels for most of the pollutants are below generally accepted exposure guidelines. The levels of carbon dioxide, carbon monoxide, and ozone were found to be below the limits set by these guidelines in all the houses studied. However, it is important to note that this study was carried out during the warmer months of the year, when houses would be expected to be less tightly sealed than they would be in mid-winter.

The U.S. Environmental Protection Agency (EPA) recommends an action level of 4 pCi/L for radon. The average level found in the 70 houses surveyed in this study was slightly

TABLE 2

Summary of Airtightness and Air Infiltration Measurements

	Mean	Maximum	Minimum	Standard Deviation
Equivalent Leakage Area (cm^2)	1038	2594	293	507
Normalized Leakage Area (cm^2/m^2)	2.904	6.266	0.696	1.371
Air Change Rate at 50 Pa (ACH)	6.84	16.95	1.63	3.35
Air Infiltration Rate (ACH)	0.29	1.35	0.00	0.22

above this—at 4.5 pCi/L—and the highest level was 16.1 pCi/L, more than four times the EPA action level. Because air infiltration from below grade is generally much greater during winter months, when wind and stack effect come into play, it is expected that the radon levels measured in the 78 houses studied would be greater during the winter months of the year.

The exposure guidelines produced by the Federal Provincial Advisory Committee on Environmental and Occupational Health in April 1987 (the Guidelines) specify an action level of 0.1 ppm for formaldehyde. The average level found in this study was 0.09 ppm, and many of the houses tested were above the action level. Two of the houses were insulated with urea formaldehyde foam insulation (UFFI) and, interestingly, the formaldehyde levels in those living areas were found to be some of the lowest measured in this study. However, one of these houses did have a heat recovery ventilator unit.

The Guidelines specify an acceptable long-term exposure range (ALTER) of less than 0.04 mg/m^3 for respirable suspended particulates (RSP) and a short-term range of less than 0.10 mg/m^3. The instrument used in this study was not sensitive enough to detect RSP at 0.04 mg/m^3, but it indicated eight living rooms at higher levels than the short-term exposure range out of 55 houses in which this measurement was made. In most of these houses with high RSP levels, there were smokers present.

The Guidelines do not specify an acceptable long-term exposure range for ozone since there are insufficient data to serve as a basis for establishing an ALTER. However, it is important to note that trace amounts of ozone were detected only in houses with electrostatic air cleaners.

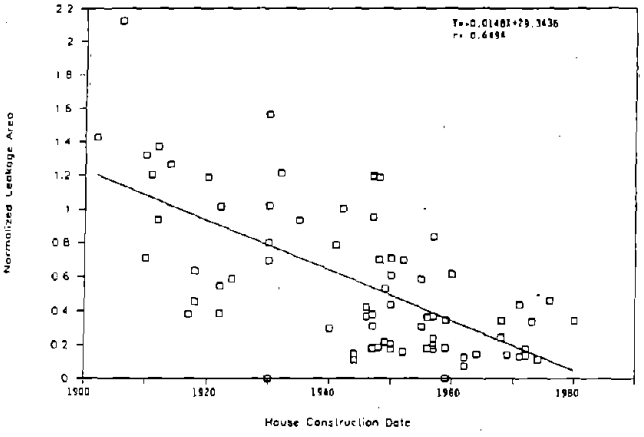

Figure 3 House construction date vs. airtightness using normalized leakage area

Table 2 summarizes the results from the airtightness measurements made on 76 of the 78 houses surveyed in terms of equivalent leakage area, normalized leakage area, and air exchange rate at 50 Pascals depressurization. In relative terms, the latter two are of greater importance when comparing and correlating data. Normalized leakage area relates buildings by floor area, and air exchange rate at 50 Pascals depressurization relates buildings by internal volume. The results from the air infiltration measurements made are also contained in this table. However, the results of these measurements were highly dependent on the weather conditions at the times of testing, and are only of importance when they are compared with predicted air infiltration (from airtightness information and local weather data). Figure 3 shows the relationship between house construction date and airtightness for 76 of the houses surveyed. Figures 4 and 5 show the relationships between measured and predicted air infiltration using the Sherman and Shaw models, respectively.

A homeowner survey report containing several data items was completed for each house. These included house identification; personal data about the occupants; energy conservation features of the house; several indoor air quality questions; questions about moisture problems; questions

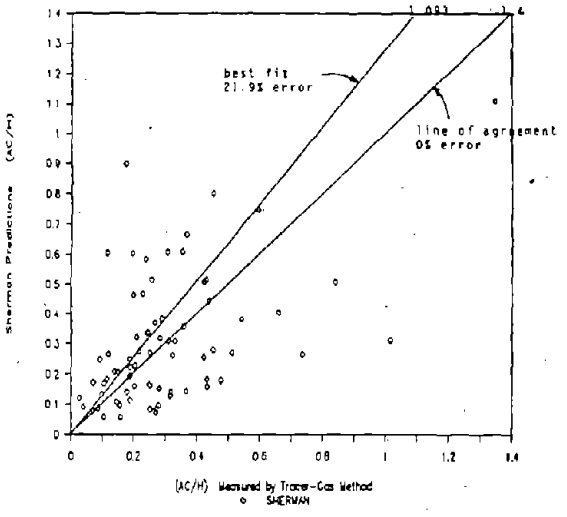

Figure 4 Sherman model predictions vs. measured air exchange rates

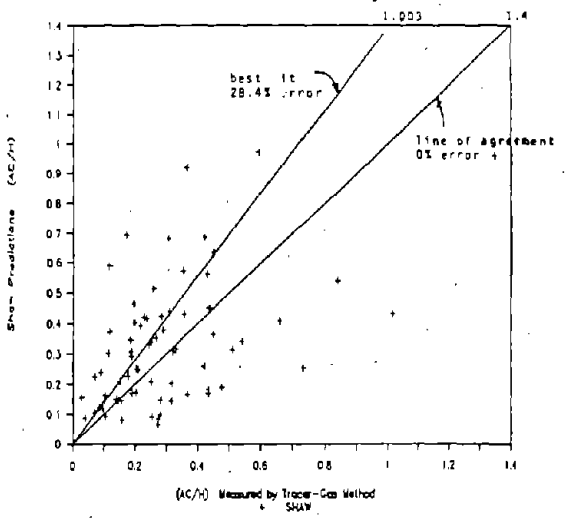

Figure 5 Shaw model predictions vs. measured air exchange rates

about heating, ventilating, and air-conditioning equipment; and questions about fan use. Information of greatest interest obtained from this survey was whether or not occupants were concerned about the air quality in their homes. Of the 78 houses surveyed, occupants of 32 of these houses—or 41%—were concerned about their indoor air quality. While there was no general correlation between census district and occupants' concern about indoor air quality, the highest income district expressed the greatest concern about indoor air quality. In this district, the occupants in five out of six houses surveyed were concerned about their indoor air quality.

Prior to the 78-house study, it was anticipated that exhaust fans in residential houses are frequently not used because occupants object to their noise. From information in the homeowner survey report and the measured sound pressure levels of exhaust fans in the surveyed houses, this was found not to be the case. No correlation was found between actual sound pressure level and perceived fan noise. Occupants who were concerned about their air quality were found to use their exhaust fans whether they perceived them to be noisy or not.

DISCUSSION AND CONCLUSIONS

The Winnipeg survey generated a set of approximately 750 observations and measurements of characteristics of a set of 78 randomly selected houses. As would be expected from such a large volume of data, many interesting ways of correlating pairs of variables develop. However, because many of the correlations were weak, they have not been presented in this paper.

These weak correlations may be due to the total randomness of the study. There was no consistency in the types of heating, ventilating, and air-conditioning equipment in the houses surveyed. There was also no consistency in the times that tests were carried out, since visits to the houses were made at the homeowners' convenience. Occupants' attitudes toward air quality in their homes differed; therefore, some of their practices, such as opening and closing of windows and usage of exhast fans, differed. Some stronger correlations did exist. However, most were related to tests that had specific procedures such as airtightness and air infiltration, and were therefore beyond the control of the occupants present.

Because instantaneous measurements were used to determine the air quality in the houses surveyed, the results are not necessarily representative of any of the houses in particular. They are meaningful, however, when using them to determine the overall averages of the pollutant levels in the 78 houses surveyed. Figure 6 shows the relationship between carbon dioxide generated per occupant vs. ventilation rate in terms of normalized leakage area (based on floor area). While there is a considerable scatter of the individual data points, the trend of lower CO_2 concentration with higher ventilation rates is clearly defined.

From the results of the air quality measurements made, it is clear that the city of Winnipeg has notably high radon levels. The average level recorded for 70 of the houses surveyed was 4.5 pCi/L, and the highest level recorded was 16.1 pCi/L. The relationship between radon level and normalized leakage area for 70 of the 78 houses surveyed is shown in Figure 7. Figure 8 is a histogram showing the distribution of the radon levels in the houses surveyed. No strong correlations existed between radon level and house age, style, or location in the city.

The random selection procedure produced a sample of houses from some of the lowest income districts, and from one of the wealthiest districts in the city of Winnipeg. Apart from obtaining generalized results about air quality in the Winnipeg housing stock, some interesting information about attitudes toward indoor air quality were obtained. Occupants of houses in the wealthier districts expressed greatest concern about the air quality in their homes and were the most willing to participate in the survey. Occupants of houses in the middle- and low-class districts were indifferent, with only 35% of the houses having occupants expressing concern. However, some of the occupants in these districts who were not con-

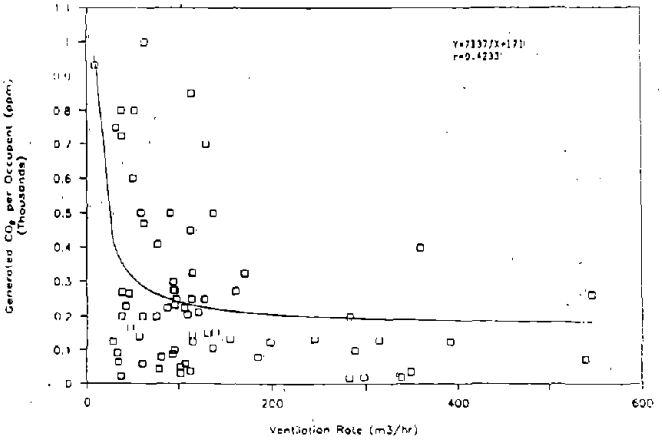

Figure 6 CO_2 per occupant vs. ventilation rate

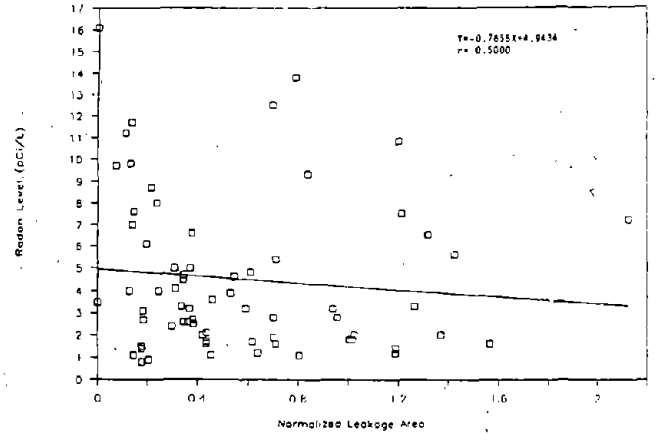

Figure 7 Radon level vs. normalized leakage area

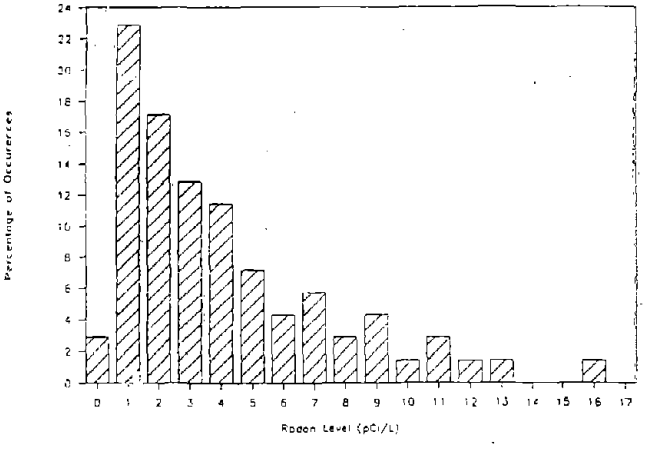

Figure 8 Distribution of radon levels

cerned were the most reluctant to allow the survey team to enter their home. There was an obvious correlation between willingness to participate in the survey and concern about indoor air quality, so the level of concern in the low-income districts might have been even lower if the number of refusals had been less. Their reluctance to participate may have been reflected in their negative responses in the homeowner questionnaire.

ACKNOWLEDGMENTS

This work was supported by the Canada Mortgage and Housing Corporation; National Research Council Canada; Manitoba Department of Energy and Mines; Public Works Canada; Energy, Mines and Resources Canada; and Manitoba Hydro.

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DISCUSSION

William Turner, Harriman Associates, Auburn, ME: What were typical noise levels and the minimum detectable level of the measurement instruments?

G.K. Yuill, G.K. Yuill & Associates Ltd., Winnipeg, Manitoba, Canada: The sound level measurement instrumentation had dynamic ranges of 36 to 140 dB for the linear weighting scale and 15 to 140 dB for the "A" weighting scale. The instrumentation was accurate to ±1 dB under specified reference conditions. Typical background readings were 30 dB and 56 dB for "A" weighting and linear weighting scales, respectively. Typical total noise levels were 60 dB and 68 dB for "A" weighting and linear weighting scales, respectively.

VENTILATION RATES IN OFFICE BUILDINGS

Andrew Persily
ASHRAE Member

ABSTRACT

The ventilation rate of an office building impacts the building air quality in terms of both thermal comfort and pollutant levels. Although office building ventilation systems are generally designed to provide specific amounts of ventilation under given conditions of weather and occupancy, the actual ventilation rates can be very different from the building design values. These differences between design and performance occur for a variety of reasons involving the design, installation, maintenance, and operation of the equipment, as well as interactions between the ventilation system and the building structure. Actual, measured ventilation rates in office buildings are required to compare the ventilation performance to design rates and ventilation standards, and to provide realistic inputs for models that predict pollutant levels, estimate pollutant exposures, and calculate thermal loads in buildings.

The National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) has been studying ventilation in office buildings for several years. This research has included the measurement of ventilation rates in 14 office buildings for periods on the order of one year, and has produced a data set of about 3000 ventilation measurements under a range of weather and building operation conditions. These data are a unique source of actual ventilation rate measurements in office buildings, and are the subject of this paper. Although measurements in only 14 buildings are insufficient to make generalizations regarding the impact of building age, construction, ventilation system type, and building location, these data do provide an indication of current practice. Although the ventilation rates vary considerably among the buildings and for each individual structure, many of the buildings have ventilation rates below recommended levels and/or design values during significant portions of the year.

INTRODUCTION

Air exchange is required in buildings in order to provide acceptable air quality in terms of indoor contaminant levels and thermal comfort. Although a specified level of air exchange does not guarantee acceptable air quality without the control of pollutant source strengths, ventilation standards and guidelines exist for most building types. For example, ASHRAE Standard 62, Ventilation for Acceptable Air Quality (ASHRAE 1989), specifies minimum levels of outdoor air intake for various space types. This standard is based on maintaining a comfortable interior environment, free from contaminant irritation and adverse health effects. It cannot, however, guarantee the maintenance of acceptable indoor air quality in the presence of unusually high contaminant sources. The ASHRAE standard specifies 10 L/s (20 cfm) per person in general office space with different recommendations in spaces such as conference rooms, reception areas, and bathrooms. HVAC design specifications for office buildings, in addition to specifying the airflow rates for each air-handling system, specify the minimum amount of outdoor air intake for these systems. These minimum amounts are generally based on some guideline, such as the ASHRAE standard.

In recent years, air exchange rates have been measured in several office buildings using tracer gas techniques (Persily and Grot 1985). The National Institute of Standards and Technology (NIST) has made measurements of air exchange in 14 office buildings, monitoring each building over about one year and making more than 3000 air exchange measurements. This paper summarizes the results of these measurements and compares the results to recommended levels of ventilation and to each building's minimum outdoor air intake specifications. In most of the office buildings studied, the measured air exchange rates are below recommended levels and/or design values during a significant portion of the building's occupied hours.

OFFICE BUILDING VENTILATION

All of the buildings discussed in this paper, and most modern office buildings in North America, are mechanically ventilated. The purpose of these ventilation systems is to provide conditioned air in order to maintain the interior air temperature and relative humidity at comfortable levels for the building occupants, as well as to maintain appropriate conditions for equipment and materials within the building. In addition, mechanical ventilation is intended to provide sufficient outdoor air to keep various indoor contaminants at acceptable levels. The net air exchange rate of an office building includes both the outdoor air intake associated with the mechanical ventilation system plus the rate of infiltration of outdoor air through the building envelope.

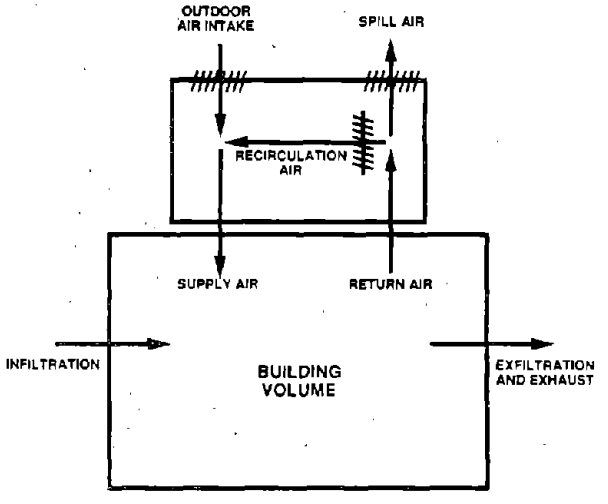

Figure 1 Schematic of a building ventilation system

National Institute of Standards and Technology, Gaithersburg, MD.

TABLE 1

Basic Building Information

Building	Year of Construction	Number of Stories	Floor Area (m^2)
A	1974	7	71,000
B	1987	7	46,000
C	1969	15	28,000
D	1984	3	12,100
E	1984	3	12,100
F	1981	7	66,400
G	1982	5	14,600
H	1977	2	1,900
I	1978	8	18,600
J	1978	4	6,900
K	1972	5	3,600
L	1977	15	20,700
M	1975	4	5,300
N	1981	6	48,500

TABLE 2

Description of the Buildings Mechanical Ventilation Systems

	Supply Fan Capacity		Minimum Outdoor Air Intake		
Building	Air changes per hour	(cfm/ft^2)	Air changes per hour	(cfm/ft^2)	Percent of Supply Air
A	*	*	*	*	*
B	3.0	(.61)	*	*	*
C	1.7	(.24)	1.70	(.24)	100%
D	4.3	(.92)	0.72	(.15)	16%
E	4.3	(.92)	0.72	(.15)	16%
F	4.1	(.82)	*	*	*
G	2.9	(.63)	*	*	*
H	3.1	(.77)	0.42	(.10)	13%
I	2.5	(.43)	*	*	*
J	3.1	(.67)	1.82	(.40)	60%
K	5.5	(1.78)	0.90	(.29)	16%
L	3.8	(1.27)	0.36	(.12)	9%
M	2.4	(.80)	0.53	(.17)	21%
N	2.8	(.55)	0.36	(.07)	13%

* Information unavailable.

The rate of air exchange associated with a mechanical ventilation system (see schematic in Figure 1) is determined by a control system that varies the position of outdoor air intake, recirculation, and exhaust dampers within the air-handling system, and may also vary the fan airflow rates. There are a wide variety of air-handling systems and associated controls, but the systems in modern North American office buildings are generally of two basic types—constant volume and variable air volume (VAV). In a constant-volume system, the supply fan always moves the same amount of ventilation air and the temperature of this supply air is varied to meet the space-conditioning load within the building. In these systems, the amount of outdoor air intake is modulated by varying the position of the intake, recirculation, and exhaust dampers. Regardless of the amount of outdoor air intake, these dampers are always supposed to be positioned such that the supply airflow rate minus the return airflow rate is maintained at a constant level. This difference is intended to provide make-up air for toilet and other exhausts, and to maintain a slight positive pressure across the building envelope to control infiltration. These damper positions may be modulated by an automatic control system that responds to changes in indoor and outdoor air temperature and humidity, or they may be controlled manually by the building operator.

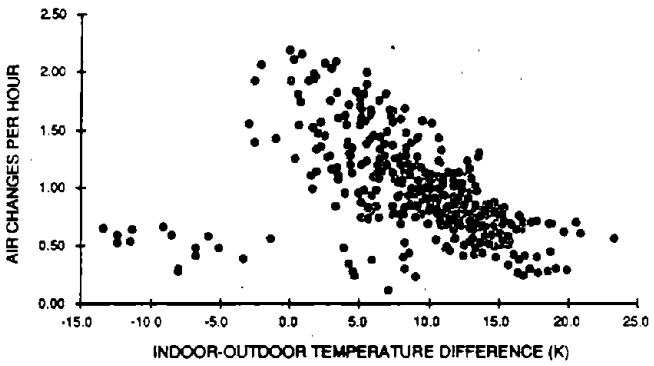

Figure 2 Air exchange rate vs. indoor-outdoor temperature difference for Building B

In variable-air-volume systems, the supply air temperature is kept constant and the supply airflow rate into the building is varied to meet the space-conditioning load. VAV systems are more common in newer buildings for reasons of reduced energy consumption and better control of local environmental conditions. The outdoor air intake control in VAV systems is essentially the same as in constant-volume systems, in that damper positions modulate in order to vary the air intake rate. Regardless of the mode of operation, both types of systems are always supposed to supply the minimum amount of outdoor air specified in the ventilation system design.

There are basically three modes of outdoor air intake control, corresponding to hot, cold, and mild outdoor air temperatures. Figure 2 is a plot of the air exchange rate data for Building B (one of the buildings discussed in this paper) vs. the indoor-outdoor air temperature difference. During hot weather, the amount of outdoor air intake is generally minimized to control the space-conditioning load within the building. During mild weather, outdoor air may be used to cool the building (a so-called economizer cycle), although some building air-handling systems are not equipped to take advantage of such "free-cooling." Most systems cut back the outdoor air intake to a minimum level during very cold weather in part to protect the heating and cooling coils in the air-handling systems from freezing.

In addition to the intentional outdoor air intake through the ventilation system, the net air exchange rate of a mechanically ventilated building also includes unintentional infiltration of air through leaks in the building envelope. The amount of envelope infiltration depends on the envelope airtightness and the strength of the infiltration driving forces,

i.e., indoor-outdoor air temperature differences, wind, and mechanical equipment operation. In the design and operation of most modern, mechanically ventilated office buildings, the rate of envelope infiltration is generally assumed to be negligible. In fact, measurements and modeling of air exchange in office buildings has shown that envelope infiltration rates are often the same order of magnitude as the rates of intentional outdoor air intake (Persily 1985; Persily and Norford 1987). Although the envelope infiltration rate of an office building may be large enough to meet the outdoor air intake requirements of that building, infiltration air should not be relied upon for ventilation since its rate cannot be predicted, the incoming air is neither conditioned nor filtered, and there is no control over the distribution of this air within the building.

The air exchange characteristics of every building are unique due to differences in outdoor air intake controls, system operation schedules, envelope airtightness, and interior configuration. These factors determine the air exchange rate of a building at any given time and the distribution of air exchange rates over time. As mentioned above, the air intake rate through the mechanical ventilation system is determined by the time of day and season, as well as by the weather. The envelope infiltration rate is also determined by the weather, as well as by the operation of the mechanical ventilation system (itself a function of time and weather). Therefore, in order to characterize a building's air exchange performance, many air exchange measurements are required over a range of outdoor environmental conditions and times of day and season. The air exchange rate during minimum outdoor air intake conditions is of particular interest in characterizing air exchange in a building. The distribution of the building's air exchange rates over a year, specifically the amount of time that the building operates at this minimum level of ventilation, is also important.

DESCRIPTIONS OF THE BUILDINGS

This section provides a brief description of each of the 14 buildings studied by the NIST, including information on their air-handling systems, outdoor air intake controls, and specified design levels of minimum outdoor air intake, if available. These buildings are denoted as Buildings A through N, and Table 1 presents some basic information for each building. All but one of these buildings are less than 20 years old, and they range in floor area from about 2000 to 70,000 m² (about 22,000 to 750,000 ft²). These are the total conditioned floor areas of the buildings (including corridors and lobbies), as opposed to rentable or occupiable floor areas. Buildings A and B, and G through N are federal office buildings, while Building F is a state office building. Buildings C through E are privately owned, although Building C is leased to the federal government. All of the buildings contain predominantly office space, with Building A containing some laboratories.

Basic information on the mechanical ventilation systems for each of the 14 buildings is presented in Table 2. All of the buildings have VAV systems, except for Buildings C and K, and all of the VAV systems employ economizer cycles. Most of the VAV buildings have constant-volume air handlers serving some of the smaller areas within the buildings, such as lobbies. Building C has a constant-volume system with 100% outdoor air intake, with no capability of recirculating air. Building K also has a constant-volume system. The amount of outdoor air intake in the building is modulated manually, with the building operator adjusting this proportion based on the interior and exterior environmental conditions.

Table 2 lists the supply fan capacity and the minimum outdoor air intake rate for each building, where available, in units of air changes per hour (ach) and in cfm/ft². The minimum outdoor air intake as a percentage of the total supply air is also given. These quantities are based on the mechanical equipment specifications for each building. The fan capacity in the VAV systems is the maximum capacity, which may not necessarily be realized in practice. The fan capacity in air changes per hour is simply the specified airflow rate divided by the building volume. The volume used is the total floor area from Table 1 multiplied by the ceiling height. In all buildings except C, this ceiling height includes the return air plenum due to the fact that return air is recirculated in all of these buildings. In Building C there is no return air plenum and the ceiling height of the occupied space is used. For all of the buildings except Building K, the fan capacity is between about 2 and 4 ach. The supply airflow rate per unit floor area is between 0.5 and 1 cfm/ft² in most of the buildings, with Building C below this range and Buildings K and L above it. The minimum outdoor air intake rate is generally between 1/3 and 1 ach. The specifications for Building J yield a minimum outdoor air intake rate of 1.82 ach, which is probably an error in the specifications. Building C has a minimum outdoor air intake rate of 1.7 ach, but since this building always operates at 100% outdoor air intake, this number is reasonable. Other than Building C (with 100% outdoor air intake) and Building J (with a suspected error in the ventilation specifications), the outdoor air intake for all of the buildings is between about 10% and 20% of the supply airflow rate.

AIR EXCHANGE MEASUREMENT TECHNIQUE

The air exchange rates in these buildings were measured using the tracer gas decay technique. This technique has been used for many years in both residential and commercial buildings to determine air exchange rates (ASTM 1983; Hunt 1980; Persily 1988). In this procedure, a harmless and nonreactive tracer gas is released into the building and mixed thoroughly with the interior air. Once the tracer gas concentration within the building is uniform, one monitors the decay in tracer gas concentration over time. The rate of decay of the logarithm of concentration is equal to the air exchange rate of the building during the time of the test. It is crucial that the tracer gas be uniformly mixed with the interior air such that the tracer gas concentration within the building can be characterized by a single value. If these conditions of uniform concentration are not achieved, then the measurement results are not valid.

In these measurements, sulfur hexafluoride (SF_6) was injected into the building supply fans in a manner that facilitated achieving a uniform tracer gas concentration within the building. The tracer gas was then allowed to mix for a period from 20 minutes to one hour, depending on the building. Different amounts of time were required to achieve a uniform concentration of tracer gas within each of the buildings, due to differences in air distribution systems, interior configuration, and ventilation system airflow rates among the buildings. In order to verify that a uniform tracer gas concentration had indeed been achieved, the concentration was sampled at many locations within each building. The rate of tracer gas concentration decay at each of these air sample locations was determined over a period of one to two hours, during which time the exterior and interior environmental conditions and fan operation status were monitored and recorded.

TABLE 3

Summary of Building Air Exchange Measurements

Building	Number of Measurements	Mean Air Exchange Rate	Median Air Exchange Rate
A	228	1.73	1.65
B	392	0.97	0.41
C	521	0.90	0.91
D	544	0.99	0.94
E	536	0.80	0.72
F	127	1.15	1.12
G	93	0.89	0.90
H	94	0.78	0.50
I	175	0.75	0.67
J	93	0.29	0.25
K	52	0.54	0.40
L	131	0.73	0.65
M	46	1.19	0.96
N	90	0.99	1.07
All Buildings	3122	0.94	0.89
All Buildings Except A and C	2373	0.88	0.80

These measurements employed microcomputer-based, automated tracer gas measurement systems that controlled the tracer gas injection, the air sampling, and the tracer gas concentration measurement, and recorded the tracer gas concentrations, the environmental conditions, and the fan operation status. These systems ran unattended and were capable of monitoring 10 air sampling locations, with the tracer gas concentration at each location being monitored once every 10 minutes. In buildings in which 10 air sample locations were insufficient to characterize the interior tracer gas concentration, more than one of the automated systems were employed.

RESULTS

Hundreds of tracer gas decay tests were conducted in each of these 14 buildings for a total of more than 3000 air exchange measurements. Tests were conducted in each building for at least one month during each season of the year, with some buildings tested for longer periods. No special equipment operation schedules were employed during these tests, i.e., the buildings were occupied and operated in the same manner as would have occurred had the measurement equipment not been installed. Even with the large number of measurements made in each building, the data set for each building is not necessarily representative of the building's average performance due to the dependence of air handler operation and air exchange rate on exterior weather conditions. Although the results cannot be interpreted to yield rigorous measures of the building's average or typical performance, they still may be expected to provide approximations of the building's typical air exchange rates. The more data points collected for a building, the better these data can be expected to approximate the building's average air exchange performance.

Figures 3 through 16 show air exchange rate frequency distributions for each of the buildings, and Table 3 shows each building's mean and median air exchange rate. In the figures, the vertical axis is the number of measured air exchange rates in each 0.25 ach interval of air exchange rates. The table contains the mean and median air exchange rate of each building and of all the buildings together, as well as the number of measurements made in each building.

Most of the frequency distributions can be characterized as "log normal," with a predominance of lower air exchange rates. Such a distribution is characterized by a median value that is below its mean. Those buildings with a large number of measurements clearly exhibit this trend, e.g., Figures 4 (Building B), 6 (D), and 7 (E). Buildings with a smaller number of measurements are more apt to exhibit a "scattered" distribution of air exchange rates, e.g., Figures 10 (Building H), 11 (I), and 15 (M).

The air exchange rates for some of the buildings, due to unique characteristics of their ventilation and control systems, yield distributions that are different from the log normal distribution seen in the buildings with automatically controlled VAV systems. For example, the air exchange rates measured in Building C (see Figure 5) are almost all in the range from 0.75 to 1.0 ach, with about one-third as many between 1.0 and 1.25. The data from Building C exhibit this distribution because the building has a constant-volume air-handling system with 100% outdoor air intake. The relatively small number of air exchange rates below 0.75 ach occurred during extreme weather conditions (either very hot or very cold) when the air handlers are turned off, presumably to reduce the space-conditioning load of the building. Building K, in Figure 13, is the only other building with a constant-volume

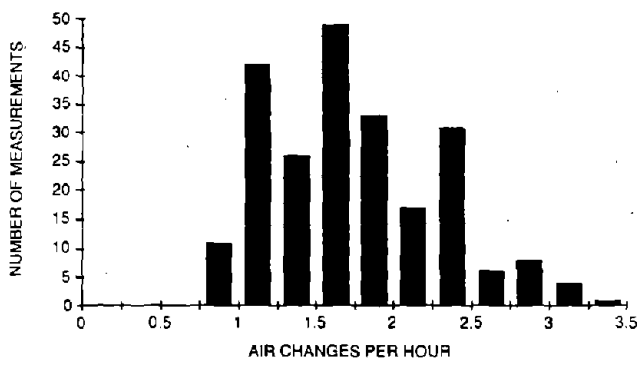

Figure 3 Frequency distribution of air exchange rates in Building A

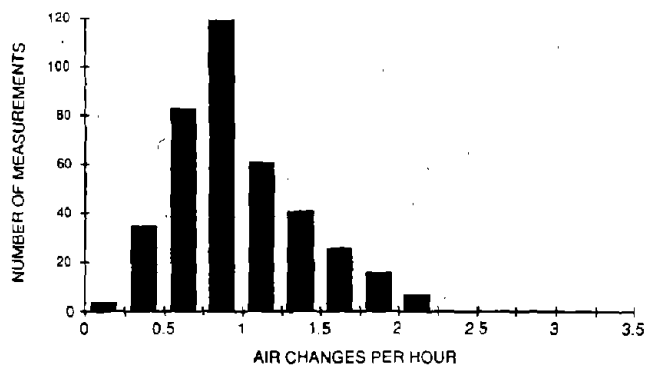

Figure 4 Frequency distribution of air exchange rates in Building B

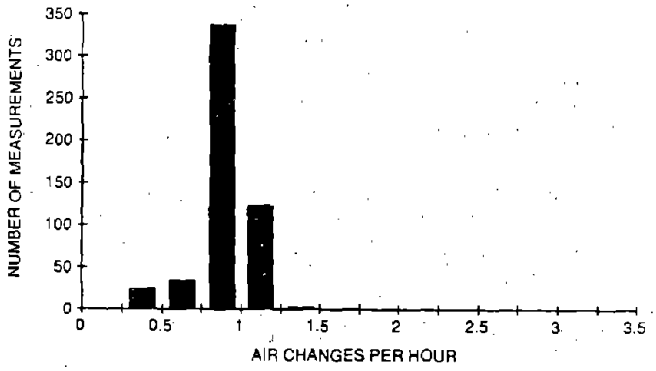

Figure 5 Frequency distribution of air exchange rates in Building C

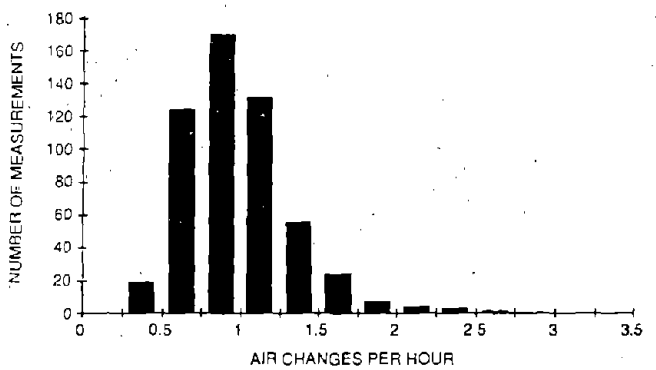

Figure 6 Frequency distribution of air exchange rates in Building D

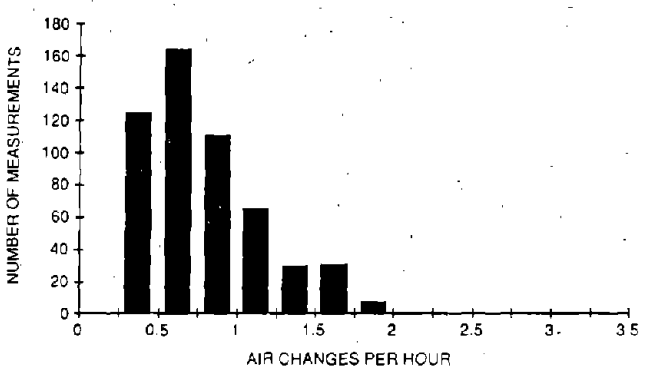

Figure 7 Frequency distribution of air exchange rates in Building E

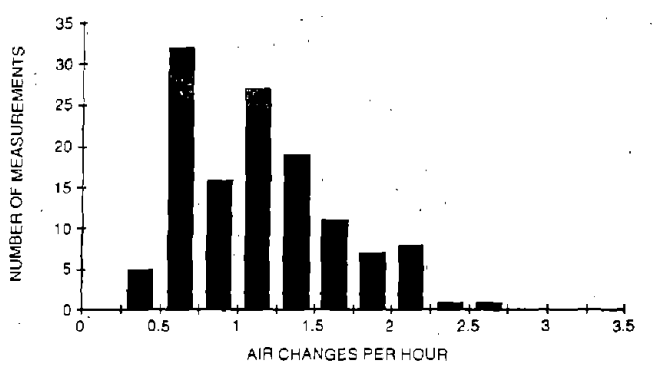

Figure 8 Frequency distribution of air exchange rates in Building F

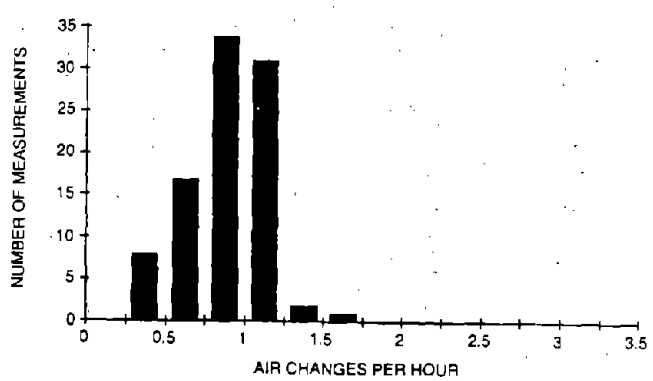

Figure 9 Frequency distribution of air exchange rates in Building G

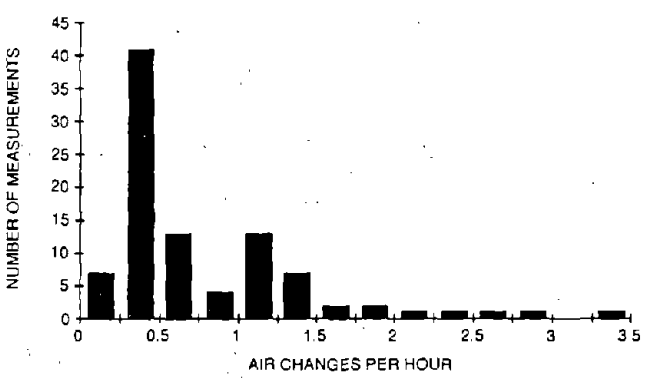

Figure 10 Frequency distribution of air exchange rates in Building H

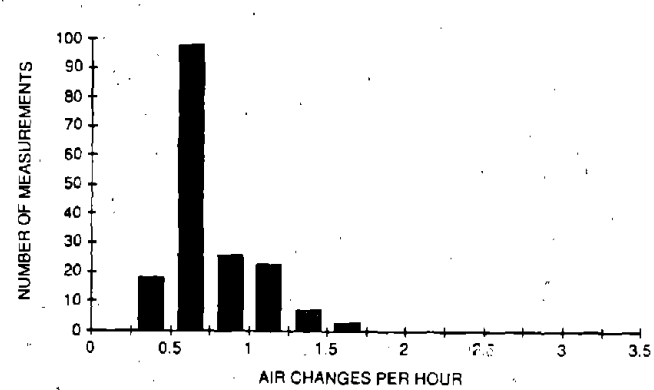

Figure 11 Frequency distribution of air exchange rates in Building I

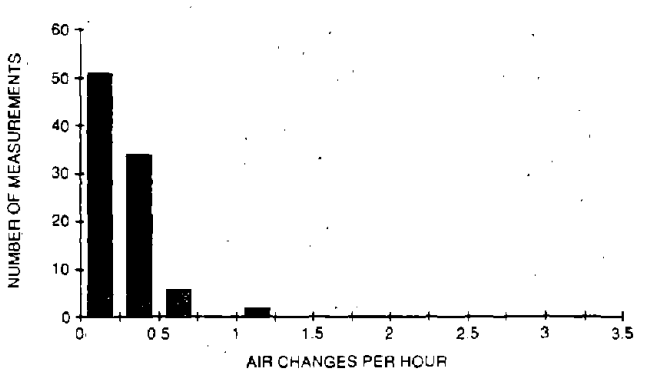

Figure 12 Frequency distribution of air exchange rates in Building J

air-handling system and it exhibits a predominance of air exchange rates less than 0.5 ach. The data above 1.0 ach were collected under extremely windy conditions when the envelope infiltration rate of the building was very large, making the total air exchange rate much larger than the mechanical ventilation system's contribution.

About half of the buildings have mean and median air exchange rates between about 0.9 or 1.0 ach. Buildings H, J, and K have median air exchange rates of less than 0.5. Building A has much larger air exchange rates than the other buildings—a mean of 1.73 and a median of 1.65 ach. As noted above, Building C also has an unusual distribution of air exchange rates, due to its unique air-handling system. Because Buildings A and C have very different air exchange characteristics from the other 12 buildings, the data from these two buildings are neglected in some of the analyses that follow. The ventilation characteristics of the remaining 12 buildings appear to be fairly typical of modern mechanically ventilated office buildings.

Figure 17 is a frequency distribution of the measured air exchange rates in all of the buildings, and Figure 18 is the distribution without Buildings A and C. The effect of the large number of measurements in these two buildings, and their higher values relative to the other buildings, is evident in comparing these two figures. The mean air exchange rate for all of the buildings is 0.94 ach, and the median is 0.89. Neglecting the data collected in Buildings A and C, the mean air exchange rate is 0.88 ach and the median is 0.80. Because there are a different number of measurements in each building, these "all-building" distributions are biased by the data from those buildings with larger numbers of measurements. In order to avoid this bias, each building's distribution was normalized by dividing the number of measurements in each range by the total number of measurements in the building. These values were then multiplied by 100 to yield the distribution that would have existed had there been 100 measurements in each building. These distributions were then combined to yield the "unbiased" distributions in Figures 19 and 20.

The above distributions of air exchange data provide useful statistical information on the air exchange rates that occur in these particular buildings, but the question remains of how these measured values compare to the minimum ventilation levels specified for each building and to recommended levels of ventilation. The specified level of minimum outdoor air intake for each building is given in Table 2 in units of ach. The recommended minimum level of outdoor air intake in ASHRAE Standard 62 (ASHRAE 1989) is 10 L/s (20 cfm) per person. In the previous version of the standard (ASHRAE 1981) there were two levels, depending on whether smoking was permitted in the space. When smoking was permitted, the level was 10 L/s (20 cfm) per person, and when there was no smoking the minimum level of outdoor air intake was reduced to 2.5 L/s (5 cfm) per person. Other levels of interest include 5 L/s (10 cfm) and 7.5 L/s (15 cfm) per person. The latter value is the amount of ventilation required to keep the steady-state carbon dioxide concentration below 1000 ppm given the CO_2 generation rate associated with one person. The former value is employed in other ventilation guidelines.

These ventilation recommendations can be converted to ach by making assumptions about the building volume associated with one person. The ASHRAE standard recommends that one assume an occupant density of seven people

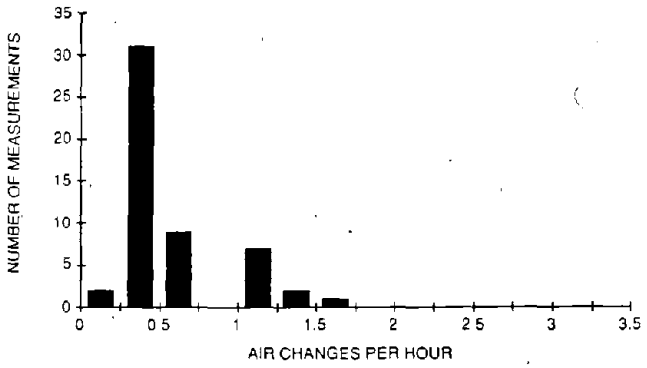

Figure 13 Frequency distribution of air exchange rates in Building K

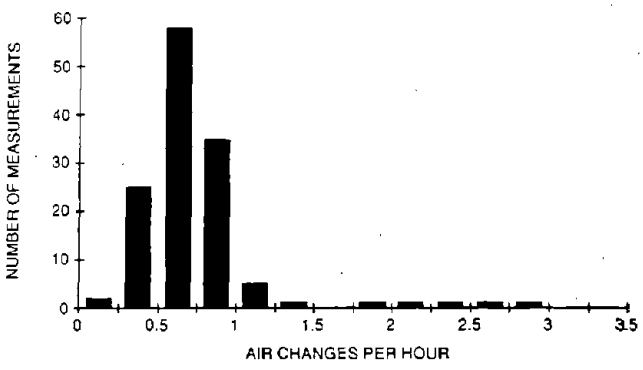

Figure 14 Frequency distribution of air exchange rates in Building L

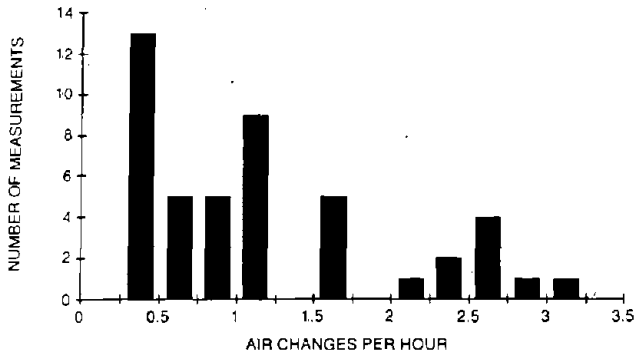

Figure 15 Frequency distribution of air exchange rates in Building M

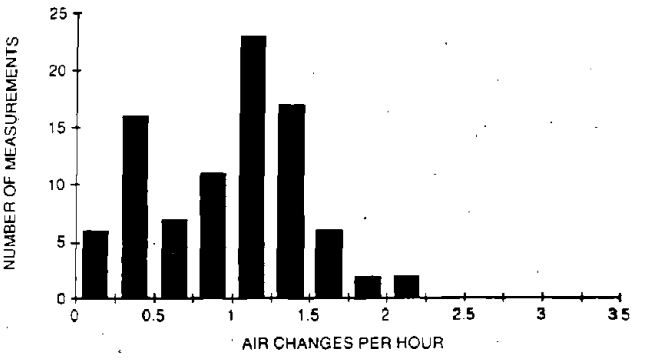

Figure 16 Frequency distribution of air exchange rates in Building N

TABLE 4

Ventilation Levels in Air Changes per Hour

Ventilation per Person	Ceiling Height of 3.5 m (11.5 ft)	Ceiling Height of 2.44 m (8 ft)
10 L/s (20 cfm)	0.72	1.03
7.5 L/s (15 cfm)	0.54	0.77
5 L/s (10 cfm)	0.36	0.52
2.5 L/s (5 cfm)	0.18	0.26

These calculated air exchange rates are based on an assumed occupant density of 7 people per 100 m^2 (1000 ft^2).

per 100 m^2 (1000 ft^2), unless a more accurate value is available. Therefore, the volume associated with one person is 14.3 m^2 (143 ft^2) multiplied by the ceiling height of the space. In most modern office buildings, there is a return air plenum above the suspended ceiling through which the interior air flows back to the air-handling system. Since this return air is generally recirculated into the supply airstream, the ceiling height employed in this volume calculation should include the height of this plenum. A typical ceiling height in this case is 3.5 m (11.5 ft).

Table 4 contains the four recommended levels of ventilation in units of ach for a typical ceiling height in an office building employing a return air plenum, and for the ceiling height in Building C, which does not have a return air plenum. The ASHRAE standard of 20 cfm per person converts to 0.72 ach in a typical office building, and 1.03 ach in Building C. These values are approximate due to the assumed values of occupant density and ceiling height.

Referring back to Table 2, in which the available ventilation system design specifications were given for the buildings, we can compare the specified levels of minimum outdoor air intake to the "standard" levels in Table 4. Buildings D and E have minimum outdoor air intake levels corresponding to 10 L/s (20 cfm) per person, while the levels in Buildings L and N correspond to 5 L/s (10 cfm). Building M is at 7.5 L/s (15 cfm) per person and Building H is somewhat less than this level.

The calculated air exchange rates in Table 4 were compared with the measured values in the 14 buildings and the results are shown in Table 5. This table shows the percentages of air exchange measurements in each of the buildings that are below 10, 7.5, 5, and 2.5 L/s (20, 15, 10, and 5 cfm), respectively. These percentages are also given for all of the buildings together, both with and without Buildings A and C. Both all-building data sets, normalized to account for the different numbers of measurements in each of the buildings, are also analyzed.

TABLE 5

Comparison to Minimum Levels of Ventilation

Building	Percent of Air Exchange Rate Measurements Below Given Level: < 10 L/s (20 cfm)	< 7.5 L/s (15 cfm)	< 5 L/s (10 cfm)	< 2.5 L/s (5 cfm)	< Design Level*
A	0%	0%	0%	0%	**
B	27%	12%	4%	0%	**
C	82%	13%	5%	0%	100%
D	23%	11%	0%	0%	23%
E	49%	26%	8%	0%	49%
F	24%	7%	0%	0%	**
G	25%	10%	1%	0%	**
H	64%	57%	24%	1%	37%
I	59%	16%	2%	0%	**
J	98%	92%	81%	18%	100%
K	81%	65%	42%	0%	81%
L	60%	27%	5%	1%	5%
M	39%	35%	0%	0%	30%
N	30%	27%	16%	0%	16%
All Buildings	45%	20%	8%	1%	52%
Normalized***	47%	28%	13%	1%	49%
All Buildings except A and C	41%	23%	10%	1%	49%****
Normalized***	49%	33%	16%	2%	43%****

* Minimum level of outdoor air intake from ventilation system design specifications.
** Design value unavailable.
*** These percentages are based on a normalized distribution for each building in which there are 100 air exchange rate measurements in each building.
**** These percentages do not include the data collected in Building J, but do include the data collected in Building C.

From Table 5, it can be seen that only Building J has a significant number of measured air exchange rates below 2.5 L/s (5 cfm). Several of the buildings have a significant number

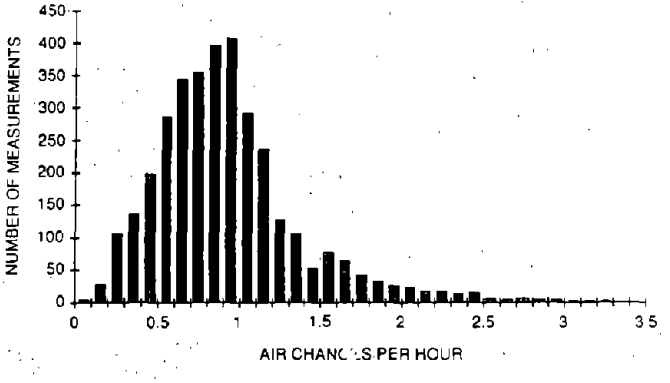

Figure 17 Frequency distribution of air exchange rates in all buildings

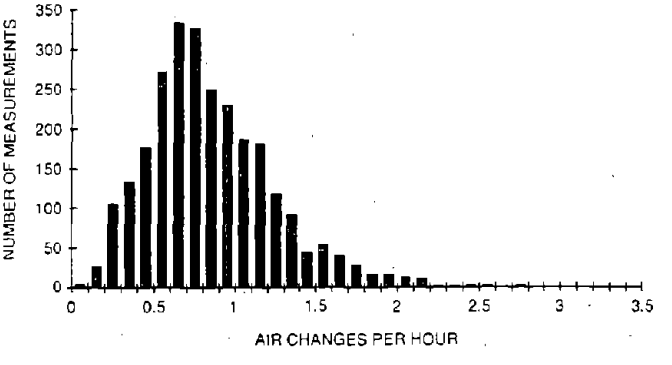

Figure 18 Frequency distribution of air exchange rates in all buildings except A and C

of measured air exchange rates below the three higher ventilation levels. Building A, with its unusually high air exchange rates, was always above 10 L/s (20 cfm) per person. More than 40% of the measured air exchange rates in all of the buildings are below the ASHRAE standard's recommendation of 10 L/s (20 cfm). Correcting for the different number of air exchange rate measurements in each of the buildings, and neglecting the data for the two buildings (A and C) with unusual air exchange characteristics, this percentage increases to almost 50%.

The last column of Table 5 shows the percent of measured air exchange rates in each building that are below the building's design level for minimum outdoor air intake. The data from Buildings C and J are always below the design level, with varying percentages in the other buildings for which a design value was available. Considering all of the data in all of the buildings, 52% of the measured air exchange rates were below their design values. Normalizing to account for the different numbers of measurements in the buildings reduces this percentage to 49%. The design specification for the minimum level of outdoor air intake in Building J is suspected of being an error, as mentioned earlier, and therefore these percentages are also given for all of the buildings except J. Therefore we see that these buildings, and presumably others, are ventilated at levels below their minimum outdoor air intake specifications for significant periods of time.

SUMMARY

The air exchange rates of mechanically ventilated office buildings include both uncontrolled air infiltration through the building envelope and intentional outdoor air intake through the ventilation system. The outdoor air intake rate is generally not constant, as the ventilation control system responds to weather and interior loads. However, the ventilation system is always supposed to supply a minimum amount of outdoor air. This minimum level of ventilation is part of the ventilation system design specifications and is generally based on recommendations in ventilation standards and guidelines.

The actual air exchange rate in a mechanically ventilated building is determined by the ventilation system design including the outdoor air intake controls, the system's operation schedules, the building envelope airtightness, and the interior configuration of the building. This air exchange is an inherently complex phenomenon, with proper performance requiring careful attention to the design, installation, operation, and maintenance of several systems and components. The actual air exchange rates in these buildings can be quite different from their design values, and tracer gas measurements are the only reliable way to determine the actual air exchange rates.

The NIST has studied the air exchange characteristics of 14 office buildings in the U.S. using the tracer gas decay technique, and these 3000 air exchange rate measurements constitute a unique data set. With only 14 buildings, it is impossible to make generalizations regarding the effects on air exchange of building age, construction style, and ventilation system type. Most of the buildings exhibit a log-normal distribution of air exchange rates with a median value below the mean. Some of the buildings have unique air exchange characteristics such as high or low air exchange rates compared with the other buildings, or relatively constant air exchange rates in buildings with constant-volume ventilation systems. The most significant difference in the buildings is in the air exchange rate under conditions of minimum outdoor air intake. This value is of interest in relation to both the building's design specifications and to recommended levels of ventilation.

The average air exchange rate for all of the buildings is about 0.9 ach. About one-half of the measured air exchange rates are below the buildings' minimum outdoor air intake design specifications. About 40% of the measured air exchange rates are below the 10 L/s (20 cfm) per person recommendation in the ASHRAE ventilation standard.

ACKNOWLEDGMENTS

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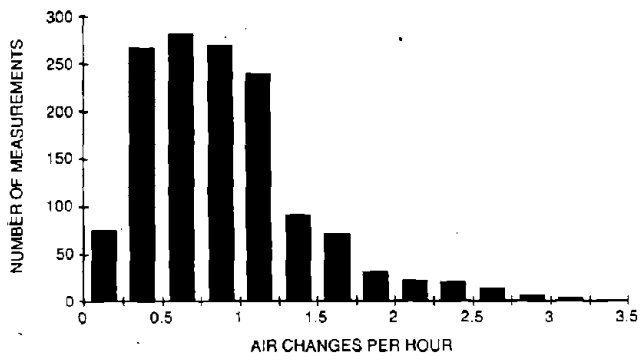

Figure 19 Unbiased frequency distribution of air exchange rates for all buildings

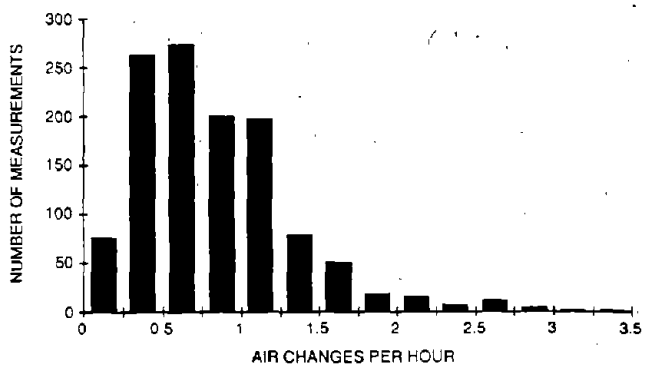

Figure 20 Unbiased frequency distribution of air exchange rates for all buildings except A and C

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DISCUSSION

Arthur E. Wheeler, Wheeler Engineering Co., Towson, MD: In calculating cfm per person from air changes per hour, how did you determine the effective building volume and number of occupants?

A. Persily, National Institute of Standards and Technology, Gaithersburg, MD: The relationship between cfm per person and air changes per hour depends on the volume assumed to be associated with each person. As discussed in the paper, I assumed an occupant density of 7 people per 1000 ft^2 and a ceiling height dependent on the buildings. If alternative assumptions are appropriate for a particular building, these calculations can easily be adjusted.

Stephen A. Roosa, ICI Americas Inc., Charlestown, IN: After having described the sample building as having high infiltration rates, can you determine or detail the relative components of infiltration and mechanical ventilation for the buildings tested?

Persily: The relative quantities of infiltration and intake in a building depend on many building-specific factors, including envelope airtightness, weather, and ventilation system zoning and operation. In one of the buildings, we have made simultaneous measurements of infiltration and intake (see Persily and Nostrand, *ASHRAE Transactions*, Vol. 93, Part 2).

Carl N. Lawson, LRW Engineers, Tampa, FL: In your study of these buildings, which type of system—VAV or CAV—seemed to function the best?

Persily: Due to the small number of buildings tested, it is impossible to make generalizations regarding ventilation system type. In fact, the type of system is probably less important than the quality of the system design, installation, operation, and maintenance.

William A. Turner, Harriman Associates, Auburn, ME: You stated that infiltration rates were significant in the study building. We have not found this to be the case in low-rise commercial buildings. Could you comment on this?

Persily: The amount of infiltration will vary significantly among buildings. Unfortunately, there is too little data to make generalizations about the effects of building type. Your results in low-rise commercial buildings could be due to reduced stack effects compared to tall buildings and/or more successful pressurization of the building interior in these buildings. Building-specific explanations require building-specific measurements.

Turner: We have found that outside air is most likely to be less than design in leaky buildings, I assume because of excess leakage at design conditions. Could you comment on this?

Persily: I find your observations interesting, though the correlation may be fortuitous rather than intentional. I find it hard to believe that building operators are making valid assessments of envelope leakage. I also find it difficult to give them credit for such conscientious efforts to control outdoor air intake rates.

Richard Gorman, NIOSH, Cincinnati, OH: How were the buildings selected for study?

Persily: Each of the buildings was studied for a different reason, ranging from poor thermal performance to indoor air quality complaints. Some were tested due to unique design features. Only two of the buildings were characterized by a large number of indoor air quality complaints.

James E. Woods, Honeywell Indoor Air Quality, Golden Valley, MN: Congratulations on an excellent presentation on data that are important to improving our knowledge of objective measures of ventilation. Would you please comment on the influence of multiple systems within a building and of multiple zones within a system (i.e., on ventilation efficiency)?

Persily: Although the tracer gas decay measurements are based on an assumption of the building being a single, well-mixed zone, there are certainly cases in which the supply air distribution is not uniform within a building. This non-uniform distribution is sometimes due to the existence of multiple air handlers, and can also exist when there is only a single air handler. The result is that certain areas within a building (zones, floors, sections of a floor, or rooms) receive proportionally less supply air (and outdoor air) relative to other areas of the building. These variations in supply air distribution can impact thermal comfort and air quality, and new measurement techniques are being developed and applied to quantify these variations.

THE EFFECT OF VENTILATION ON THE INDOOR CONCENTRATIONS OF VAPOR PHASE ORGANIC COMPOUNDS

H.C. Shields **C.J. Weschler**

ABSTRACT

Volatile organic compounds are a potential threat to the proper operation of modern electronic equipment. The concentrations of numerous vapor-phase organic compounds within a telephone switching office have been measured during a period of minimal ventilation and during subsequent periods of moderate ventilation. These measurements were made using passive samplers to collect the organic compounds. The compounds were then identified and quantified using standard gas chromatographic/mass spectrometric procedures. For the first sampling period (June 9–July 16, 1987) the amount of outdoor air used for ventilation averaged less than 3% of the total amount of air circulated through the air-handling system. The concentrations measured under these conditions were quite high; 13 compounds had values greater than 20 μg/m³. For the subsequent sampling periods, the amount of outdoor air was increased to between 10% and 15% of the circulated air. The concentrations measured under these conditions were frequently an order of magnitude lower than those measured during the first interval. For many compounds, the indoor concentrations were comparable to, or only slightly larger than, the outdoor concentrations. These results demonstrate the importance of adequate ventilation in modern office buildings.

INTRODUCTION

Due to rising energy costs, many buildings in the U.S. have implemented energy conservation programs. These measures frequently include reductions in the amount of outdoor air used for building ventilation. However, a reduction in outdoor air can lead to increased levels of volatile organic compounds (VOC), which have indoor sources.

Within telephone switching offices there are many sources of VOC. Examples include cabling, floor tiles, carpet, wall coverings, furniture, building materials, floor wax, cleaning products, paints, and lubricants. High concentrations of volatile organic compounds are most frequently associated with "sick building syndrome" (Noma et al. 1988). However, they can also pose a threat to the proper operation of modern electronic equipment. They can promote arcing between relay contacts leading to increased contact erosion. Polymeric films derived from airborne organics can produce unacceptably high resistances between contact surfaces. Airborne organics can condense on read-write heads, increasing the likelihood of fine particles sticking to the heads, which can subsequently lead to head crashes and disc drive failures. In short, money saved on energy by reducing ventilation with outdoor air might be lost to increased costs associated with diagnosing and repairing failures of electronic equipment caused by elevated levels of VOC.

The Sheboygan Falls, WI, office is a new building that contains a digital telephone switch. It was installed during the period from December, 1986 to March, 1987, although cutover to the switch did not occur until July, 1987. Based on recommendations from the manufacturer, the switch is on a raised floor which is used as an air distribution plenum. Cool air flows directly from this false floor into and through the digital switch. Wisconsin Bell personnel were concerned that such an arrangement might lead to increased concentrations of contaminants within the Sheboygan Falls office, which, in turn, might adversely affect the operation of the switch. They requested that the authors evaluate the indoor air quality at this site.

Sampling for VOC with organic vapor monitors began on June 9, 1987. Throughout the first sampling period the office was poorly ventilated (less than 3% outdoor air). Since then, the amount of outdoor air used for ventilation has been increased, and three additional sets of VOC samples have been collected. This paper documents the reduction in VOC concentrations resulting from increased ventilation with outdoor air at the Sheboygan Falls office.

EXPERIMENTAL

The Sheboygan Falls office is a 1493 ft² (139 m²) single-story building. This includes the main switch area, the power room, the lavatory, and the janitor's closet. The total volume is 14,200 ft³ (402 m³). The power room and the janitor's closet have exhaust fans that run continuously. The former operates at 80 cfm (2.3 m³/min) and the latter at 155 cfm (4.4 m³/min). There is also an 85-cfm (2.4 m³/min) exhaust fan in the lavatory that operates only when the lights are on. Air in the building is circulated by two fan systems. Fan system 1 is rated at 1500 cfm (42.5 m³/min) and runs continuously. Fan system 2 is rated at 1650 cfm (46.7 m³/min) and runs "on demand." Fan system 2 comes on if the room temperature is greater than 76°F or if the room relative humidity is greater than 53%. During the first sampling interval in this study both fans were operating (reflecting the warm mid-summer temperatures outside). During the subsequent sampling intervals fan 2 was off for the majority of the time. During the first sampling period the outside air dampers were closed and the building was not pressurized. During the subsequent sampling periods the outside air damper for fan 1 was set for a minimum 20% outdoor air, and the building was under positive pressure.

The sampling device used in this study is an organic vapor monitor or passive sampler. The collection procedure depends on molecular diffusion for eventual contact between vapor phase compounds and the charcoal sorbent. This method has been validated for low-level sampling over extended time intervals and is applicable for concentrations spanning six orders of magnitude; reproducibility averages 13% of the mean value; and the sensitivity is excellent (0.06 μg/m³—Shields and Weschler 1987).

H.C. Shields and **C.J. Weschler** are with Bell Communications Research, Red Bank, NJ.

TABLE 1

Concentrations (μg/m³) of volatile organic compounds detected within the Sheboygan Falls, WI office (1987).

Compound	DLU 0050 6/9–7/16 < 3% OA	8/19–9/23 10–15% OA	11/3–12/9 10–15% OA
Trichloroethylene	0.83	ND	ND
Toluene	8.57	5.17	2.28
Perchloroethylene	3.13	1.33	0.77
Octane	3.18	ND	1.00
D3	0.78	ND	ND
Ethyl Benzene	8.76	7.08	2.73
Xylene (M&P)	23.72	19.75	7.80
Styrene	4.22	ND	ND
Xylene (O)	8.06	5.44	2.84
Butoxyethanol-2 (N)	3.04	ND	ND
Nonane	7.42	1.24	ND
Alpha-Pinene	20.96	ND	ND
n-Propyl Benzene	5.83	1.62	0.79
C3-Alkyl Benzene	18.04	ND	3.03
C3-Alkyl Benzene	9.06	ND	1.12
C3-Alkyl Benzene/Br. C10/B-Pinene	23.49	ND	ND
Trimethyl Benzene (1, 2, 4)	ND	2.63	3.07
Trimethyl Benzene (1, 2, 4)/ Br. C10	22.73	ND	ND
Branched Decane	4.61	ND	ND
Decane & C3-Alkyl Benzene	39.20	5.44	2.60
Branched C11	15.87	ND	ND
Branched C11	8.01	ND	ND
C4-Alkyl Benzene/Br. C11	19.93	ND	ND
C4-Alkyl Benzene/Br. C11	24.15	ND	ND
C4-Alkyl Benene/Br. C11	17.42	ND	ND
Branched C11	8.41	ND	ND
Undecane & C4-Alkyl Benzene	51.04	5.18	4.03
D5	45.45	ND	ND
Dodecane	38.58	3.90	1.25
Tridecane	45.30	4.16	0.47
D6	30.01	ND	ND
Tetradecane	27.19	10.39	1.83
Pentadecane	24.90	6.48	1.65
Diethyl Phthalate	15.48	5.78	ND
Hexadecane	4.82	6.32	5.16
Heptadecane	2.94	ND	ND
Octadecane	4.08	ND	ND

TABLE 2

Concentrations (μg/m³) of volatile organic compounds detected within the Sheboygan Falls, WI office (1987).

Compound	RR0100.01 6/9–7/16 < 3% OA	RR0100.02 8/19–9/23 10–15% OA	RR0100.02 11/3–12/9 10–15% OA
Trichloroethylene	1.84	ND	ND
Toluene	9.85	7.58	2.45
Branched Octane	0.93	ND	ND
Perchloroethylene	2.34	0.97	0.83
Octane	3.42	ND	1.38
D3	0.80	ND	ND
Ethyl Benzene	8.68	7.73	2.50
Xylene (M&P)	23.65	23.32	7.77
Styrene	4.02	ND	ND
Xylene (O)	7.96	6.69	2.04
Butoxyethanol-2 (N)	2.88	ND	ND
Nonane	6.59	1.51	ND
Alpha-Pinene	19.73	ND	ND
n-Propyl Benzene	5.59	2.58	0.56
C3-Alkyl Benzene	17.54	ND	1.50
C3-Alkyl Benzene	9.56	ND	0.68
C3-Alkyl Benzene/Br. C10/B-Pinene	20.69	ND	ND
Trimethyl Benzene (1, 2, 4)	15.35	4.52	1.30
Decane & C3-Alkyl Benzene	38.85	4.00	2.10
Branched Alkane/D4	ND	ND	10.84
Branched C11	14.49	ND	ND
Branched C11/C4-Alkyl Benzene/?	8.08	ND	ND
Branched C11/C4-Alkyl Benzene/?	9.99	ND	ND
C4-Alkyl Benzene/Br. C11	13.33	ND	ND
C4-Alkyl Benzene/Br. C11	22.91	ND	ND
C4-Alkyl Benzene/Br. C11	16.17	ND	ND
Branched C11	7.95	ND	ND
Undecane & C4-Alkyl Benzene	51.98	5.29	1.72
D5	44.02	ND	ND
Dodecane	33.58	4.40	0.51
Tridecane	31.50	4.05	0.19
D6	25.49	ND	ND
Tetradecane	19.27	2.59	0.86
Pentadecane	20.50	1.16	0.22
Diethyl Phthalate	8.69	4.80	ND
Hexadecane	4.38	ND	0.51
Heptadecane	3.81	ND	ND
Octadecane	2.50	ND	ND

Prior to analysis each badge is spiked with an internal standard, typically 5 μl of a 20 μl/10 ml cyclooctane/carbon disulfide solution. The badge is then extracted with 1.5 ml of carbon disulfide. Organic compounds contained in the extract are separated and identified using standard gas chromatographic/mass spectrometric (GC/MS) procedures.

Analyses were conducted on a gas chromatograph/mass spectrometer containing a 12 m by 0.2 mm narrow bore, cross-linked dimethyl silicone, fused silica capillary column (split operation, He column flow 1 ml/min). The injection port is held at 240°C while the temperature is programmed from 0°C to 220°C at a rate of 8°C/min. An autotune with perfluorotributylamine (PFTBA) is performed daily to calibrate the mass spectrometer.

Both laboratory blanks (unexposed monitors that remained in the laboratory during sampling) and field blanks (unexposed monitors sent into the field along with sample monitors) have been analyzed; for badges from the same production lot, the results are indistinguishable. Blank corrections were only necessary for n-alkanes between dodecane and hexadecane. Other compounds did not require corrections.

RESULTS AND DISCUSSION

Table 1 presents concentrations for more than 35 volatile organic compounds detected at frame location DLU 0050 within the Sheboygan Falls office. Values are listed for three different sampling intervals—June 9 to July 16, 1987; August 19 to September 23, 1987; and November 3 to December 9, 1987. During the first sampling interval the amount of outdoor air introduced averaged less than 3% of the total amount of air being circulated through the air-handling system (< 0.4 air changes per hour). For the subsequent two intervals the amount of outdoor air was significantly increased and averaged between 10% and 15% of the circulated air (~1.3 air changes per hour). Table 2 presents information analogous to that contained in Table 1 (same three sampling intervals), but the VOC were collected at a different location in the office. The first set of samples was collected at frame location RR0100.01 and the next two sets of samples were collected at the adjacent frame, RR0100.02. For a given sampling interval the concentrations in Tables 1 and 2 are similar, indicating that the air within the office is relatively well mixed.

A more striking comparison is that between different

TABLE 3

Indoor concentrations, outdoor concentrations, and indoor/outdoor ratios (I/O) for volatile organic compounds at Sheboygan Falls, WI from 8/19–9/23/87 ($\mu g/m^3$).

Compound	RR100.02 Indoors	RR100.02 I/O	DLU 0050 Indoors	DLU 0050 I/O	Outdoors
Toluene	7.58	1.2	5.17	0.8	6.39
Perchloroethylene	0.97	0.8	1.33	1.1	1.25
Ethyl Benzene	7.73	0.9	7.08	0.8	8.54
Xylene (M&P)	23.32	0.9	19.75	0.8	25.42
Xylene (O)	6.69	0.9	5.44	0.8	7.19
Nonane	1.51	⩾1	1.24	⩾1	ND
n-Propyl Benzene	2.58	2.5	1.62	1.5	1.05
Trimethyl Benzene (1, 2, 4)	4.52	1.9	2.63	1.1	2.39
Decane & C3-Alkyl Benzene	4.00	1.1	5.44	1.5	3.66
Undecane & C4-Alkyl Benzene	5.29	1.8	5.18	1.8	2.88
Dodecane	4.40	1.0	3.90	0.9	4.46
Tridecane	4.05	1.1	4.16	1.1	3.67
Diethyl Phthalate	4.80	⩾1	5.78	⩾1	ND

TABLE 4

Indoor concentrations, outdoor concentrations, and indoor/outdoor ratios (I/O) for volatile organic compounds at Sheboygan Falls, WI from 11/3–12/9/87 ($\mu g/m^3$).

Compound	RR0100.02 Indoors	RR0100.02 I/O	DLU 0050 Indoors	DLU 0050 I/O	Outdoors
Toluene	2.45	1.7	2.27	1.5	1.47
Perchloroethylene	0.83	5.5	0.77	5.1	0.15
Octane	1.37	2.6	1.00	1.9	0.53
Ethyl Benzene	2.50	1.1	2.72	1.2	2.36
Xylene (M&P)	7.77	1.0	7.80	1.0	7.60
Xylene (O)	2.04	0.9	2.83	1.2	2.28
n-Propyl Benzene	0.55	0.8	0.79	1.1	0.70
C3-Alkyl Benzene	1.50	0.5	3.03	1.0	2.91
C3-Alkyl Benzene	0.68	0.6	1.12	0.9	1.22
Trimethyl Benzene (1, 2, 4)	1.30	0.5	3.06	1.3	2.42
Decane & C3-Alkyl Benzene	2.09	0.9	2.59	1.1	2.43
Undecane & C4-Alkyl Benzene	1.71	1.0	4.03	2.2	1.80
Dodecane	0.50	⩾1	1.24	⩾1	ND
Tridecane	0.18	⩾1	0.47	⩾1	ND

sampling intervals in either Table 1 or 2. The increase in ventilation air from the first sampling interval to the subsequent sampling intervals has dramatically reduced the concentrations of many of the volatile organic compounds. Indeed, a large number of compounds detected during the first sampling period are below detection levels during subsequent sampling periods. These include trichloroethylene, hexamethylcyclotrisiloxane (D3), styrene, 2-butoxyethanol, alpha-pinene, an isomer of C_3-alkyl benzene, several branched decane isomers, beta-pinene, several branched undecane isomers, several C_4-alkyl benzene isomers, decamethylcyclopentasiloxane (D5), dodecamethylcyclohexasiloxane (D6), n-heptadecane, and n-octadecane. Other compounds show significantly reduced concentrations; they include perchloroethylene, the n-alkanes from octane to pentadecane, n-propyl benzene, several C_3-alkyl benzene isomers, and diethyl phthalate. On the other hand, there are

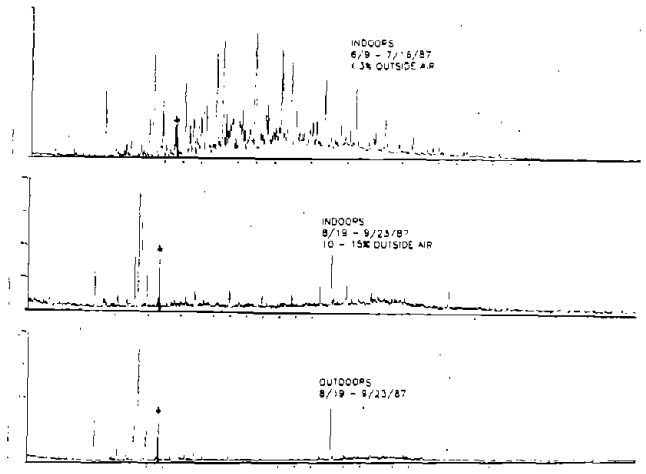

Figure 1 Total ion chromatograms for samples collected indoors (< 3% outdoor air and 10%–15% outdoor air) and outdoors at the Sheboygan Falls office. In each chromatogram the internal standard is shaded and has a small arrow above it. Many of the volatile organic compounds associated with the individual peaks are listed in Tables 1–4.

compounds which show only small concentration reductions from the first to subsequent sampling periods. These include toluene, ethyl benzene, m&p-xylene, and o-xylene. More will be said about this group of compounds below.

Figure 1 compares a total ion chromatogram (TIC) for an indoor sample collected during the "low ventilation air period" with a TIC for an indoor sample collected during an "increased ventilation air period" (August 19–September 23, 1987) and a TIC for an outdoor sample (August 19–September 23, 1987). In each TIC the peak associated with the internal standard is darkened and has a small arrow above it. The amount of internal standard is identical in each run; hence, for quantitative comparisons, the top TIC should be enlarged by a factor of 1.5. The top and middle chromatograms reveal that there is a marked reduction in indoor concentrations for many of the VOC as the ventilation air is increased. What is further apparent, comparing the middle and bottom chromatograms, is that most of the compounds that remain elevated indoors after the ventilation air has been increased are compounds with dominant outdoor sources. This point is amplified in Tables 3 and 4.

Table 3 contrasts indoor VOC concentrations measured at RR0100.02 and DLU 0050 with outdoor VOC concentrations measured at the building's air intake. Table 3 is for the period August 19-September 23, 1987, while Table 4 presents an analogous comparison for the period November 3–December 9, 1987. Each table also includes indoor/outdoor (I/O) ratios for the measured VOC. Such ratios indicate if there is a significant indoor source of an organic compound in addition to the amount of that compound that enters the building from outdoors. In Table 3 the compounds with I/O ratios greater than unity include n-nonane, n-propyl benzene, 1,2,4-trimethyl benzene, n-decane and C_3-alkyl benzene, n-undecane and C_4-alkyl benzene, and diethyl phthalate. These compounds are among the compounds in Tables 1 and 2 that decrease dramatically with an increase in outdoor air. In Table 4, fewer compounds have I/O ratios greater than 1. These include perchloroethylene, n-octane, n-undecane, and C_4-alkyl benzene. This suggests that, on average, indoor source strengths are decreasing with time. However, activities within the office do change from sampling interval to sampling interval, and some of the compounds in Table 4 with elevated

TABLE 5

Concentrations (μg/m³) of volatile organic compounds detected outdoors at the Sheboygan Falls, WI office (1987).

Compound	Air Intake 8/19–9/23	10/6–11/3	11/3–12/9
Toluene	6.39	1.89	1.47
Perchloroethylene	1.25	Ref. as IS	0.15
Octane	ND	0.75	0.53
Ethyl Benzene	8.54	3.21	2.36
Xylene (M&P)	25.42	8.46	7.60
Xylene (O)	7.19	2.76	2.28
n-Propyl Benzene	1.05	0.61	0.70
C3-Alkyl Benzene	ND	2.34	2.91
C3-Alkyl Benzene	ND	0.96	1.22
Trimethyl Benzene (1, 2, 4)	2.39	1.95	2.42
Decane & C3-Alkyl Benzene	3.66	2.61	2.43
Undecane & C4-Alkyl Benzene	2.88	1.55	1.80
Dodecane	4.46	0.98	ND
Tridecane	3.67	ND	ND
Tetradecane	1.31	ND	1.26
Hexadecane	5.41	8.37	1.74

TABLE 6

Concentrations (μg/m³) of volatile organic compounds detected at a telephone office in Neenah, Wi.

Compound	4/14–6/15/87 Indoors	Outdoors
Toluene	2.29	1.64
Perchloroethylene	0.34	0.21
Octane	0.20	ND
D3	0.49	ND
Ethyl Benzene	0.59	0.49
Xylene (M&P)	1.61	1.11
Xylene (O)	0.40	0.43
Nonane	ND	0.18
n-Propyl Benzene	0.78	0.60
C3-Alkyl Benzene	0.78	0.95
C3-Alkyl Benzene	0.85	0.89
Trimethyl Benzene (1, 2, 4)	1.67	0.99
Decane & C3-Alkyl Benzene	1.47	0.90
D4	10.85	5.43
C4-Alkyl Benzene	0.93	0.57
Undecane & C4-Alkyl Benzene	1.46	1.29
Trichlorobenzene	1.91	ND
Dodecane	1.19	1.79
Tridecane	1.25	ND
Tetradecane	ND	0.65
Dimethyl Phthalate	0.96	ND
Pentadecane	0.60	1.18
Diethyl Phthalate	0.77	ND
Hexadecane	1.30	ND
Heptadecane	1.75	ND

TABLE 7

Concentrations (μg/m³) of volatile organic compounds detected in various locations outside the Sheboygan Falls, WI office (1987).

Compound	10/6–11/3/87 Diesel Stack	Air Intake	Fr. of Bldg
Toluene	1.61	1.89	1.78
Perchloroethylene	0.80	Ref. As IS	0.86
Octane	0.70	0.75	0.80
Ethyl Benzene	2.71	3.21	3.12
Xylene (M&P)	7.88	8.46	9.24
Xylene (O)	2.35	2.76	2.57
n-Propyl Benzene	0.52	0.61	0.73
C3-Alkyl Benzene	1.97	2.34	2.58
C3-Alkyl Benzene	0.80	0.96	1.11
Trimethyl Benzene (1, 2, 4)	1.56	1.95	2.51
Decane & C3-Alkyl Benzene	1.96	2.61	2.62
Undecane & C4-Alkyl Benzene	1.33	1.55	2.20
Dodecane	0.89	0.98	1.27

I/O ratios do not have elevated I/O ratios in Table 3.

In contrast to the compounds with elevated I/O ratios, the compounds in Tables 3 and 4 that have I/O ratios close to 1 show minimal change in their concentrations in Tables 1 and 2. These include toluene, ethyl benzene, m&p-xylene, and o-xylene. The major source of these compounds within the Sheboygan Falls office is infiltration from outdoors and, consequently, ventilation will have little effect on their concentrations (see the middle and bottom chromatograms in Figure 1).

Table 5 lists outdoor concentrations of volatile organic compounds detected during three separate sampling periods at the Sheboygan Falls office. These samples were collected at the air intake. Table 6 lists outdoor concentrations of volatile organic compounds at a similar location in Neenah, WI (Weschler and Shields 1989). The outdoor concentrations for several of the compounds, including ethyl benzene and the xylene isomers, are significantly higher at the Sheboygan Falls site than at the Neenah site. Initially, a source on the grounds of the Sheboygan Falls office was suspected. One possibility was the exhaust stack for the diesel generators (emergency power), which are exercised twice a month. This stack is on the roof, set back about 10 ft from the outdoor wall that contains the air intake. To test this hypothesis, outdoor samples were collected at three different locations: next to the diesel stack, at the back of the building by the outdoor air intake, and at the front of the building. The results are presented in Table 7. The concentrations measured at the three different outdoor locations are very similar, including those for ethyl benzene and the xylene isomers. These results indicate that the elevated levels are not due to a point source on the office grounds, but instead reflect outdoor air levels in the greater Sheboygan Falls area. Discussions with local residents suggested that outdoor VOC levels may be influenced by a large coal-fired power plant located about six miles east in Sheboygan, WI. Lake-effect winds could bring the power plant plume into the Sheboygan Falls area. The higher (relative to Neenah, WI) values of ethyl benzene and the xylene isomers are consistent with such a source. Furthermore, the higher summer concentrations of these compounds, compared with middle and late fall (see Table 5), are consistent with seasonal weather patterns and perhaps an inversion layer during part of the summer sampling interval (Seinfeld 1986).

The above discussion of outdoor concentrations should not deflect attention from the central observation of this study: the very high concentrations of indoor VOC at low ventilation rates. To underscore this point, it is useful to compare *indoor* concentrations from the Sheboygan Falls office with *indoor* concentrations from the Neenah site. Indoor values at Sheboygan Falls during the first sampling interval (less than 3% outdoor air, Tables 1 and 2) are frequently 20 to 30 times larger than indoor values for the same compounds at Neenah (Table 6). For example, undecane and C_4-alkyl benzene, coeluting peaks, had a combined concentration of ~50 μg/m³ at Sheboygan Falls, compared with 1.5 μg/m³ at

Neenah; similarly, dodecane had contrasting concentrations of ~35 μg/m³ and 1.2 μg/m³; and pentadecane had contrasting concentrations of ~22 μg/m³ and 0.6 μg/m³. The sampling period at Neenah was 62 days—from April 14 to June 15, 1987. During this period the amount of outdoor air introduced averaged close to 60% of the circulated air (Weschler and Shields 1988). This reflects the air-handling system at Neenah, which has been designed to maximize the use of outdoor air. The use of such large amounts of outdoor air keeps indoor concentrations comparable to outdoor concentrations, even for compounds with significant indoor sources.

Figure 2 further amplifies the above point. The steady-state concentrations of a hypothetical vapor-phase organic compound are plotted as a function of the amount of outdoor air (percent of circulated air). These concentrations have been calculated using a mass-balance model presented in earlier studies (Weschler et al. 1988; Weschler and Shields 1989) and applied to the Sheboygan Falls office. The calculations assume that fan 1 is on and fan 2 is off (i.e., a flow rate in the plenum of 42.4 m³/min), that the building is under slight positive pressure, that the hypothetical compound has an internal generation rate of 20 g/min, and that the hypothetical compound is not present outdoors. Figure 2 indicates an indoor concentration less than 2 μg/m³ at 25% outdoor air. At 12.5% outdoor air, the concentration, 3.8 μg/m³, is still acceptable. However, the curve shows that the concentration is rising rapidly as the percent outdoor air decreases. At 1.6% outdoor air, the calculated concentration is up to 30 μg/m³ and climbing rapidly. Figure 2 clearly illustrates the consequences of inadequate ventilation when indoor sources of VOC are present.

Figure 3 is also derived from the mass-balance model. In this figure the steady-state concentrations of a hypothetical organic compound are plotted as a function of the rate at which this compound is emitted indoors. There are actually two lines corresponding to two different ventilation strategies, 1.5% outdoor air and 15% outdoor air. The other parameters in the model are identical to those used in deriving Figure 2. At 15% outdoor air, even for a source rate of 40 μg/min (very large), the calculated concentration is still less than 7 μg/m³. In contrast, at 1.5% outdoor air and the same emission rate, the calculated concentration is more than 60 μg/m³. It is evident from Figure 3 that for an office similar to that in Sheboygan Falls, 15% outdoor air provides adequate dilution of indoor pollutants even at high indoor emission rates.

These studies were initiated as a result of concern over a design feature in the air-handling system at the Sheboygan Falls office. This building uses a raised floor as an air distribution plenum (see Introduction). Cool air flows directly out of this false floor into the digital switch. Such an arrangement makes the office especially sensitive to inadequate ventilation. The concern was warranted because there are major potential sources of organic emissions in a "raised floor plenum." These include both the tiles associated with the raised floor (plasticizers) and concrete sealer or paint used on the actual floor (solvents, plasticizers, other additives). These sources have very large surface areas, and the ventilation air passes directly over them. Such an arrangement actually facilitates mass transport of outgasing organic compounds from the surface of the emitting materials. Emission rates for certain pollutants can be larger than those encountered in a building with a more traditional air-handling system. Consequently, if there is inadequate ventilation, steady-state indoor concentrations of selected contaminants can reach very high levels.

CONCLUSIONS

When the Sheboygan Falls switching office was poorly ventilated, the concentrations of numerous vapor-phase organic compounds were unacceptably high. Eighteen of the monitored compounds had concentrations in excess of 10 μg/m³. Such high concentrations can lead to failures in the sensitive electronic equipment housed within this office. For example, organic compounds can cause contact activation, or

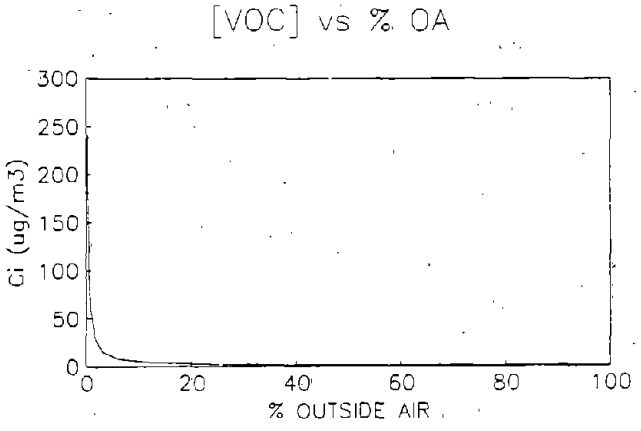

Figure 2 Plot of indoor steady-state concentration (Ci) of a hypothetical volatile organic compound vs. the amount of outdoor air used for ventilation (percent of circulated air). This plot is derived from a mass-balance expression presented elsewhere (Weschler and Shields 1989). It has been calculated assuming a flow rate in the plenum of 42.5 m³/min, an indoor emission rate of 20 g/min, and an outdoor concentration of zero.

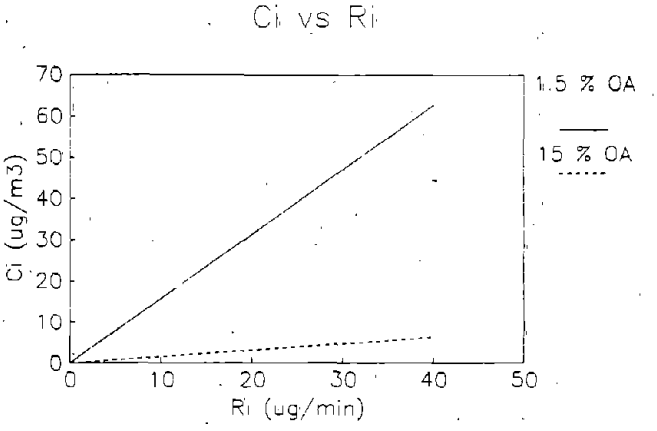

Figure 3 Plots of indoor steady-state concentrations (Ci) of a hypothetical volatile organic compound vs. its indoor emission rate (Ri). The solid line has been plotted assuming that 1.5% of the circulated air is outdoor air. The dashed line has been plotted assuming that 15% of the circulated air is outdoor air. These plots have been derived from a mass-balance model presented elsewhere (Weschler and Shields 1989). They have been calculated assuming a flow rate in the plenum of 42.5 m³/min and an outdoor concentration of zero.

the enhancement of arc duration, in telephone switching systems. For activation processes, Gray (1978) has reported a value of roughly 500 $\mu g/m^3$ as the lower critical exposure to unsaturated organic species with 10 carbon atoms. A "good housekeeping" value is one to two orders of magnitude lower than this value. Such concentrations have been achieved at the Sheboygan Falls office by increasing the amount of ventilation air to a moderate level. None of the monitored compounds currently exceeds a concentration of 10 $\mu g/m^3$. As expected, those compounds with the highest I/O ratios (i.e., those compounds with dominant indoor sources) are most affected by the ventilation rate.

The results from the Sheboygan Falls office can be explained in the context of a mass-balance model that has been presented in earlier studies (Weschler et al. 1988; Weschler and Shields 1989). Plots derived from the model illustrate the consequences of inadequate ventilation when there are indoor sources of vapor-phase contaminants. Their indoor concentrations increase sharply when the rate at which they are exhausted from the building becomes small compared to the rate at which they are emitted within the building. The model also shows that, at a building such as Sheboygan Falls, 15% outdoor air provides adequate dilution of indoor pollutants even when their emission rates are as large as 40 $\mu g/min$.

The results of this study demonstrate that, through the judicious use of outdoor air, indoor concentrations of volatile organic compounds can be maintained at levels close to outdoor concentrations. This is true even for species with significant indoor sources.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Jeff Hansen and Mike Buck of Wisconsin Bell for their valuable assistance in this project.

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DISCUSSION

William A. Turner, Harriman Associates, Auburn, ME: Could you clarify the air exchange rates at 3% and 10% to 15% outdoor air in your study buildings? Are they typical of office building air turnover rates?

H.C. Shields and C.J. Weschler, Bell Communications Research, Red Bank, NJ: As noted in the manuscript, when the amount of outside air used for ventilation averaged less than 3% of the total air being circulated in the air-handling system, the air turnover rate in the building was less than 0.4 air changes per hour. When 10% to 15% of the air being circulated through the air-handling system was outside air, the air turnover rate was approximately 1.3 air changes per hour. The latter value is slightly larger than might typically be encountered in this type of commercial building.

COMMERCIAL APPLICATIONS OF RADON MITIGATION TECHNIQUES

J.G. Davidson

ABSTRACT

Whether it be on schools or office buildings, very little commercial building mitigation work has been performed thus far on a regional or national basis. But just as residential mitigation has become commonplace, commercial building mitigation will become routine in the near future. In dealing with existing commercial buildings or with commercial buildings under construction, new mitigation techniques will be evolving, as will the retrofitting of residential techniques for commercial application. The following presentation is the result of a recent commercial mitigation in New Jersey.

INTRODUCTION

In March 1987 a large corporation conducted its own Working Level (WL) measurements at one of its facilities in northern New Jersey. The daughter measurements were made over a 24-hour period using Working Level (WL) monitors. Two measurements were made, each in the lower level of the building with a lab area registering .069 WL and an office area measuring .083 WL. At these levels, corporate management felt it needed to undertake remediation, which it initially performed itself. Remediation consisted of sealing all floor cracks, sealing the perimeter wall/slab joint, and painting the block walls. Retesting indicated no change in radon levels, so the company felt the need to call in a professional radon remediation company. The building was examined in September 1987. After a walkthrough of the facility, additional testing and a diagnostic evaluation were recommended. These were performed in late December 1987.

The Building

A two-story building, partially built into a bank, the building was constructed of 12 in concrete block and was completed in 1955. The building was 118 ft long and 36 ft wide. It had 6600 ft² of interior space, the lower level being a lab area having been altered many times, and the upper level being office space. There was also a 1500 ft slab-on-grade conference room. There was no central forced heating or air-conditioning, the heating being baseboard radiation and the air-conditioning consisting of window units. In the lab areas there were no fume hoods. (See Diagram 1.)

Retesting

Retesting consisted of testing every lower-level room with charcoal canisters, as well as the first floor slab-on-grade conference room. Exposure time for the charcoal canisters was four days, with testing being performed in December. These results are as follows:

Location	*Original Reading*
Lab I	51.6 pCi/L
Lab II	40.8 pCi/L
Lab III	36.6 pCi/L
Furnace Room	23.1 pCi/L
Generator Room	36.1 pCi/L
1st Floor Conf. Room	22.1 pCi/L

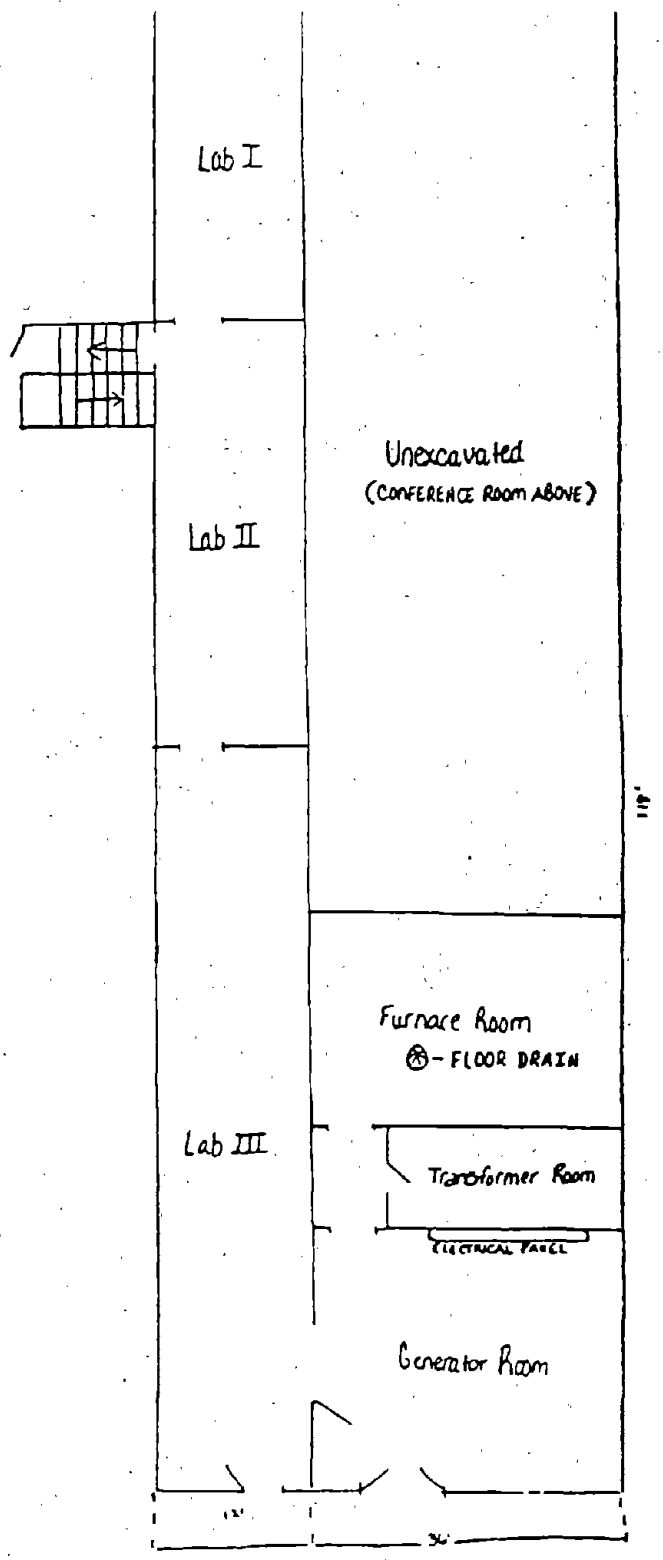

Diagram 1

When these measurements were seen, a thorough diagnostic investigation was begun.

Diagnostic Measurements

A visual examination of wall entry routes revealed numerous pipe openings and penetrations in the block, open pipe sleeves to the exterior ground, openings around electrical conduits, and openings around an air shaft duct.

Slab entry routes were minimal except for a floor drain in the furnace room that emptied into a dry well. Here, a grab air measurement was performed which indicated more than 1000 pCi/L. There was also a condensate line emptying into a large open drain pipe.

A number of sub-slab gas samples were collected. These were obtained by drilling a 3/8 in hole through the slab, after which gas was drawn into a cell and analyzed. This is a standard diagnostic technique.

Communication tests were performed in many areas of the slab, but communication was almost non-existent. Freon, being used as a tracer gas, was also injected with little or no transmission under the slab. Maintenance personnel said this was due to large 3 ft by 3 ft sub-slab piers that were poured for heavy equipment to rest on, which caused interference with communication and subsequent pressure field development.

Gas samples were also taken from cavities inside the painted block walls and ranged from 25 to 1200 pCi/L.

Conclusions for Selection of Mitigation Techniques

Because a pressure field could not be developed, it was decided that remediation would have to be through wall ventilation. Channel venting initially was considered; however, there was a considerable amount of large research equipment obstructing the path that could not be disturbed. The only alternative was block wall ventilation on a large scale. Reservations were expressed with this technique because it was a two-story block building. Wall communication tests were performed with vacuum suction and smoke and adequate communication was found in all walls, which was surprising because the wall expanse was so large. Using a rheostat on the vacuum, suction was adjusted for 2 in of water but, at this pressure, communication was poor. This was especially noticeable when the P measurement at 2 in of water dropped off by a factor of 20 in 25 ft (to .1 in water). It was therefore decided that, to achieve better communication, the area of the block from which suction was to be drawn would have to be cut back.

Remediation, therefore, began with hiring a foam insulation contractor to foam the course of block 7 ft from the floor around the entire exterior of the building, as well as the center interior partition. All block cores were drilled, but a mistake was made which was discovered afterward—not drilling and foaming the 1/2 cores at the ends of the block where the mortar joints were.

After the foaming was completed, all other entry routes were sealed, including jackhammering out the floor drain and installing an airtight trap. Communication tests were then performed using a micromanometer and it was discovered that communication was improved by a factor of 2. This then led the team to design the appropriate number of suction points and fans needed. (See Diagram 2.) Communication tests above the foam line also indicated that there was some leakage of the system, which indicated that the 1/2 cores at the mortar joint had not been foamed. Cost, however, pre-

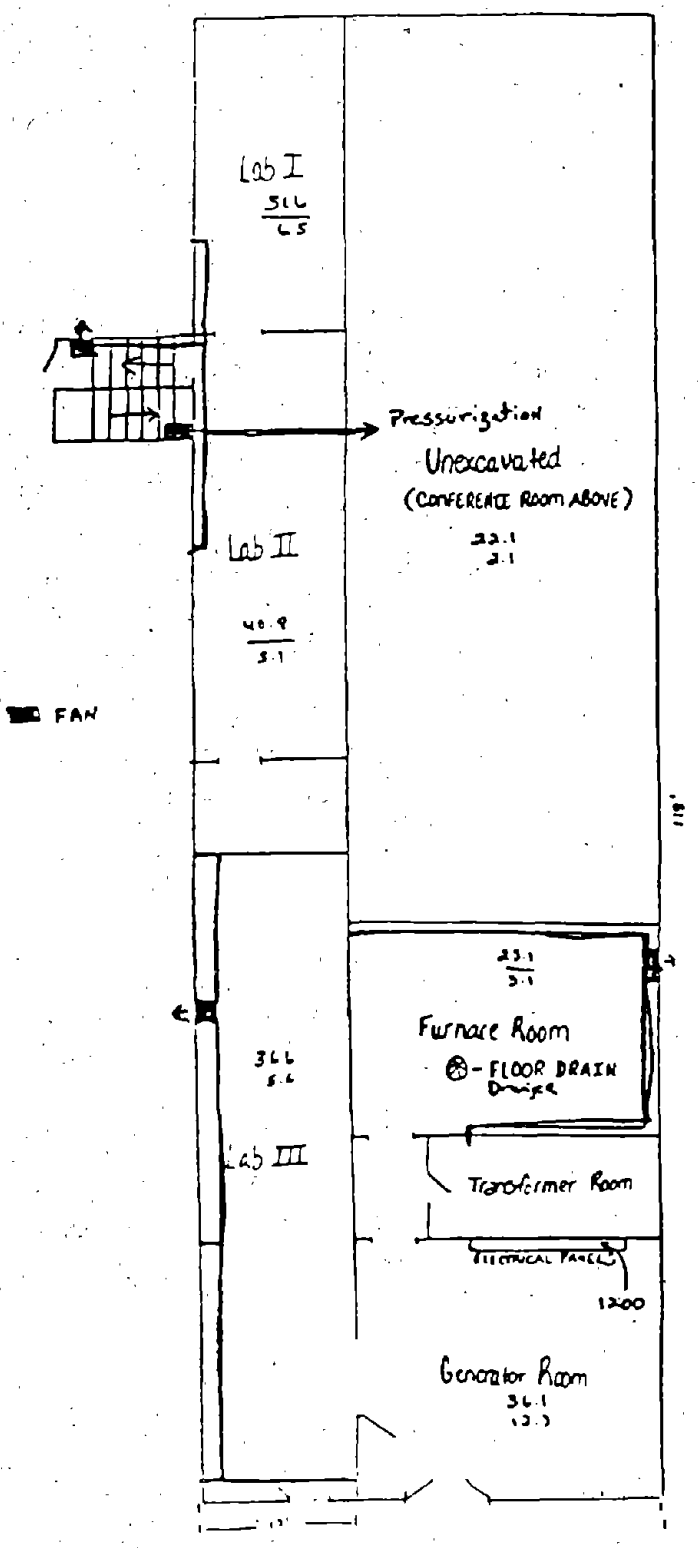

Diagram 2

Shows 3 blockwall suction systems and 1 pressurization system.

Numbers indicate radon levels (in pCi/L) prior to and after remediation.

vented this from being done. It was decided to install three wall depressurization systems and, as an experiment, a pressurization system was installed for the area under the conference room slab. From the building investigation, it was apparent that openings through the conference room slab were all sealed. If the pressurization system did not work, the second alternative was depressurization. It was hoped that the space could be pressurized with about 10 pascals. Using a micromanometer and a rheostat on the fan, levels were obtained that fluctuated between 8 and 15 pascals on a regular basis.

After the systems were operational, the areas were retested with charcoal canisters. This testing took place in March with the following results:

Location	*Reading with System*
Lab I	6.5 pCi/L
Lab II	5.1 pCi/L
Lab III	5.6 pCi/L
Furnace Room	3.1 pCi/L
Generator Room	12.3 pCi/L
1st Floor Conf. Room	2.1 pCi/L

Why were the levels in the generator room not significantly reduced? A full diagnostic work-up was performed again, which included freon tests, suction tests of the wall with smoke, gas samples from the walls, etc. What was interesting was that none of the walls had any significant radon levels. Gas samples then were taken from the electrical conduits in the room and it was found that there were more than 1200 pCi/L coming from the open conduits in the electrical panel boxes. These were then sealed with a one-part urethane foam. The final testing is not available at this time, but all rooms were expected to be below the EPA guidelines of 4 pCi/L.

Energy Considerations

The four in-line fans that were installed in this project were 1.8 amps (198 W). The life expectancy as per the manufacturer is 10 to 12 years. At 1 in static pressure, each fan will consume 82 W per day, or 718 kW per year. At a national average of $.05 per kW, the yearly cost would be $35.92 per fan.

Mitigation Costs to Consumer

All testing, diagnostic evaluations, and subsequent remediation cost the consumer $21,000. The foam insulation work cost the contractor $2400. The four systems that were installed as well as the sealing process took five men five days. Diagnostic time spent investigating the problem was about two days for two men.

So What Was Learned?

1. In some cases, residential remediation techniques can be applied to commercial buildings.
2. Foaming courses of block is an expensive procedure but, if done properly, can be very effective.
3. Large inaccessible areas can be successfully mitigated with pressurization.
4. Even the best-laid plans of experienced mitigators can be undone if a source is missed and the problem is not totally diagnosed.

CONCLUSION

Not all non-residential buildings will call for these techniques. Recently, an extensive mitigation was performed on four schools in which mitigation was successful but took a totally different approach. Commercial mitigation is going to be the new frontier of radon and the next few years should prove quite exciting.

GLOSSARY

1. Working Level (WL) measurements—a unit of measurement for documenting exposure to radon decay products. 1 Working Level is equal to about 200 pCi/L.
2. Communication Tests—communication tests are used to determine the ease or difficulty with which gas can move through the soil and aggregate under the slab or within a cavity such as a block wall. Typically two holes are drilled 20 ft apart and suction applied to one hole while micromanometer measurements are made at the other.
3. Pressure field development—refers to suction points located in the slab or wall that have the ability of drawing and maintaining suction at other various points remote from the suction point.
4. Channel Venting—a sheetmetal baseboard duct is installed around the entire perimeter of the basement (including interior block walls) and covers the joint between the floor and wall. Holes are drilled through the interior face of the block at intervals inside this baseboard, and the wall is ventilated by depressurizing the baseboard duct with fans.

VERIFICATION AND USES OF THE ENVIRONMENTAL PROTECTION AGENCY (EPA) INDOOR AIR QUALITY MODEL

L.E. Sparks B.A. Tichenor M.D. Jackson J.B. White

ABSTRACT

This paper describes a set of experiments used to verify an indoor air quality (IAQ) model for estimating the impact of various sources on indoor air quality in a multi-room building. The model treats each room as a well-mixed chamber that contains pollutant sources and sinks. The model allows analysis of the impact of room-to-room airflows, HVAC (heating, ventilating, and air-conditioning) systems; and air cleaners on IAQ. The model is written for personal computers.

The experiments were conducted in a test house. Three different pollution sources were used in the experiments—moth crystals, kerosene heaters, and dry-cleaned cloths. The model predictions were in good agreement with the experimental data, especially when a sink term was included in the model.

The paper presents a brief discussion of the theory on which the model is based. Preliminary data and theory of sources and sinks are also discussed. Examples demonstrating the use of the model to analyze IAQ control options and to estimate exposure from a pollutant are included.

INTRODUCTION

Indoor air quality (IAQ) is determined by the interactions of sources, sinks, and air movement between rooms and between the building and the outdoors. Sources may be located in rooms, in the HVAC system, or outside the building. Sinks (i.e., materials that adsorb indoor pollutants) may be located in the same locations. Sinks may also act as sources when the pollutant concentrations drop below a given value.

Air movement in a building consists of:

1. Natural air movement between rooms.
2. Air movement driven by a forced-air (HVAC) system.
3. Air movement between the building and the outdoors.

A model to describe indoor air pollution must include all three types of air movement. The model must also be able to describe the behavior of sources which may be time dependent. Finally, the model must be able to include the effects of sinks. This paper describes a personal-computer-based model, INDOOR, that includes all these factors.

OTHER INDOOR AIR MODELS

Indoor air quality models can be divided into two basic classes—micro models and macro models. The micro models are designed to analyze the details of the airflow in a building and solve the Navier-Stokes equations. Macro models are designed to analyze the bulk room-to-room flow of air and pollutants and solve the differential equations derived from overall mass balances. INDOOR is a macro model designed to run on a personal computer.

TABLE 1

Representative List of Indoor Air Quality Models

Author	Reference	Comments
Axley and Grote	1	PC Based Multizone.
Ryan et al.	2	Airliner cabin 4 zones.
Rodgers	3	2 zones.
Ishizu & Kaneki	4	Multizone.
		Traynor
	5	Single zone long term.

Model references:
1. General Indoor Air Pollution Concentration Model (Phase II Report). J. Axley and R. Grote, Washington, DC: U.S. Department of Commerce, National Bureau of Standards (1986).

2. P.B. Ryan, J.D. Spengler, and P.F. Halfpenny, *Atmos. Envir. 22* (6), 1031 (1988).

3. L. Rodgers, *ASHRAE Trans. 86* (Part 2), 92 (1980).

4. Y. Ishizu and K. Kaneki, *Trans. SHASE No. 24*, 24 (1984).

5. G. Traynor, Presentation at Symposium on Indoor Pollutant Sources and Sinks, Gaithersbury, MD (1989).

INDOOR is one of several macro models for describing indoor air quality. Many of these models are not generally available and were developed for specific purposes. A representative list of other macro models is given in Table 1.

The features that set INDOOR apart from most of the models listed in Table 1 are:

1. Ease of use.
2. Incorporation of source and sink terms.
3. Incorporation of air cleaners.
4. Incorporation of strong ties between source studies and test house studies.

THEORY

The full description of the model is given by Sparks (1988) so only a brief overview will be given here.

The pollutant concentration in a room is calculated by a mass balance of the various pollutant flows. For the single room shown in Figure 1:

Amount in − Amount out + Amount produced − Amount removed = Amount accumulated

The analysis can be extended to multiple rooms by writing a mass balance equation for each room and the building as a whole. The result is a system of equations. One constraint on the equations is that the mass of air entering a room must equal the mass of air leaving a room. Another constraint is that the mass of pollutant must be conserved for the building as a whole.

The type of mixing between the pollutant and the room air must be specified before the mass balance equations can

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be used in a model. Because mixing is complex, the exact mixing cannot be specified; simplifying assumptions must be made. Plug-flow and well-mixed are two common mixing possibilities.

In the plug-flow mixing model, the pollutant concentration varies from point to point along the airflow path. In the well-mixed model, the pollutant concentration is the same for every point in the room. Experimental data from test houses show that pollutant concentration does not vary significantly from point to point in a room—especially on a time scale of several minutes, which is the time scale of interest for the computer model. Therefore, the well-mixed assumption was used in the IAQ model.

Once the mixing is defined, the various mass balance equations discussed above can be used to write a set of differential equations. The equation for a single room is:

$$VdC/dt = C_oQ_{in} + P - S - CQ_{out}$$

where V is the volume of the room, C is the room concentration at time t, C_o is the concentration outside the room, Q_{in} is the flow entering the room, P is the mass produced, S is the mass lost to the sink, and Q_{out} is the airflow leaving the room. For multiple rooms, the single equation is replaced by a system of equations.

The equations for the IAQ model can be solved numerically by a number of standard techniques. A modified midpoint method described by Press et al. (1987) is used in the model. This method is faster than fourth-order Runge Kutta for the same accuracy. The modified midpoint method is stable for reasonable values of the step size used in the calculations. The program monitors the behavior of the solution and, if instability is detected, a warning message is printed. The user must reset the step size and restart the calculations.

SOURCE TERMS

The source term is the most important factor in determining the concentration of pollutant. The source term is defined as the amount of material emitted by the source per unit time. The source term is calculated by multiplying the source size by the source emission rate. The source emission rate is the amount of material released by a unit source per unit time. The current version of the model uses empirical factors for the emission rates from the sources. The emission rates for most of the sources in the model are based on chamber studies conducted by the Environmental Protection Agency. As additional data are acquired from these chamber studies, they will be added to the data base supporting the model.

Sources can be divided into several classifications based on the time dependency of the emission rate. The classifications used in the model are:

1. Random short-term on/off sources (e.g., cigarettes).
2. Long-term on/off sources (e.g., heaters).
3. Long-term steady-state sources (e.g., moth crystals).
4. Sources with high initial emission rates that decay with time (e.g., floor wax).

The model accommodates all these possibilities in an idealized fashion.

Although the empirical emission factors appear to work well in the model, emission rates based on an understanding of the pollution sources would be more generally useful. Theoretical emission rates would allow analysis of sources that have not been studied in chambers, for example. Limited work is under way to develop such models. These models are based on analysis of the mass transfer processes that occur at the source. Preliminary results of modeling of moth crystals and solvents provide predictions that are in good agreement with experimental data.

Sinks

Sinks are surfaces and materials that remove pollutants from the indoor air. The material collected by the sink may remain in the sink or be reemitted later. Although the importance of sinks in determining indoor air quality is generally recognized, there are few data on the behavior of sinks.

A simple model of sink behavior is used in the IAQ model. The rate of material to the sink, R_{sink}, is assumed to be:

$$R_{sink} = k_{sink} C A_{sink}$$

where k_{sink} is the rate to the sink (units length/time), C is the pollutant concentration in the room, and A_{sink} is the area of the sink. This equation can be rewritten as

$$R_{sink} = ueCA_{sink}$$

where u is the deposition velocity and e is the efficiency of the sink. If $e = 1$, all the pollutant that hits the sink sticks and if $e = 0$ none of the material that hits the sink sticks. The deposition velocity can be estimated from the diffusivity of the pollutant (Sparks 1988). For many volatile organic compounds (VOC) the deposition velocity is in the range of 0.2 to 0.3 m/h. For particles the deposition velocity is about 0.05 m/h.

Sinks can reemit some or all of the material collected in them. The emissions from the sink can be estimated by:

$$E_{sink} = k_eM_{sink}A_{sink}$$

where E_{sink} is the emission rate from the sink, k_e is an emission rate constant for the sink, and M_{sink} is the mass collected in the sink. Research is under way to determine k_e and to better understand sink emissions.

AIRFLOWS

The airflow in a building consists of forced airflows due to the HVAC system and natural airflows due to normal temperature and pressure differences within a building. These airflows determine how pollutants are dispersed in a building. When the airflows are dominated by HVAC flows, the HVAC flows can be measured and used in the model. If measurements are not available, design HVAC airflows, or airflows calculated based on ASHRAE guidelines, can be used. If all else fails, a rule of thumb that an HVAC provides about 5 to 7 air changes per hour (ach) can be used. Note that only a fraction of the HVAC airflow is fresh outside air; the bulk of the HVAC airflow is recirculated air.

When airflows are not dominated by the HVAC system,

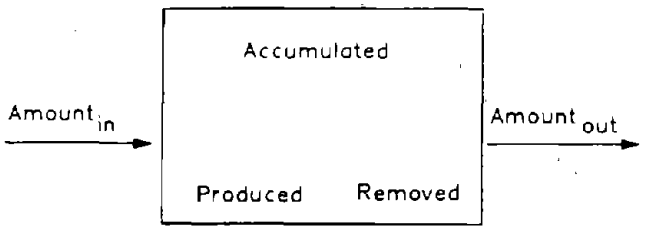

Figure 1 Single-room airflows

estimates of the room-to-room airflows are needed. There are few data available on these flows. Data based on limited measurements indicate that if doors between rooms on the same floor of a building are open, the room-to-room airflows for these rooms are several air changes per hour. Data with doors closed and for airflows between floors are not generally available. Airflows between floors in a multi-story building are generally much less then the room-to-room airflows. Analysis of very limited data indicates that floor-to-floor airflows in a residence might be 30 to 40 m^3/h and in a larger building might be up to 90 m^3/h.

Note that although the room-to-room airflows are important, they do not have to be known with high precision. For example, calculations show that for the case of a strong source in a small room, a factor of 10 change in airflow between the room with the source and an adjoining room changes the concentration in the room with the source by about a factor of 2 and the concentration in the other rooms by less than 50%.

MODEL VERIFICATION

Experiments to verify the model were conducted in a test house (see Figure 2 for a floor plan). The pollutant sources for the experiments were moth crystals, dry cleaning, and kerosene heaters. In all three cases the pollutant emission rate was determined from chamber experiments. House characterization and each of the experiments are discussed briefly below.

House Characterization

Experiments were conducted to estimate the overall air exchange between the house and the outdoors, the room-to-room airflows, and the HVAC airflows. Some of these experiments were qualitative in nature and were designed to test the reasonableness of the values used in the model.

Air exchange with the outdoors was determined by blower door tests and SF_6 tracer studies. The agreement between the two methods was quite good. The overall air exchange between the outdoors and the test house was 0.35 h^{-1} for most of the conditions encountered in the experiments discussed below. The air exchange rate was 0.4 h^{-1} for the kerosene heater tests. The increase in air exchange rate for the kerosene heater test was caused by opening a window 5 cm. SF_6 measurements were commonly made for all experiments to ensure that the default value had not changed.

The HVAC airflows were determined by measuring the HVAC airflow into each room and the overall return air. The two airflows balanced within 10%. Because many of the experiments were conducted with the HVAC fan on, the HVAC

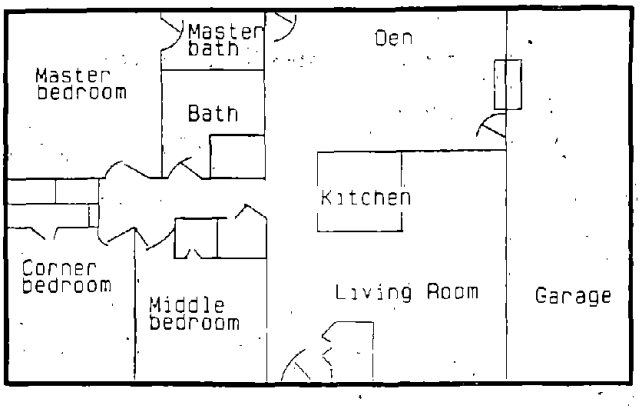

Figure 2 Test house diagram

TABLE 2

Comparison of Measured and Predicted p-dichlorobenzene Concentrations.

Room	Measured ug/m^3	Predicted ug/m^3
Closet	74	74
Corner bedroom	5.1	5.7
Master bedroom	3.8	4.0
Den	3.7	4.0

airflows provided the dominant airflow pattern for the house. This pattern was HVAC flow into each room and flow from each room into the hall and then to the HVAC return. The HVAC provided about 6 air changes per hour for each room.

Although the HVAC airflow provided the dominant airflow pattern for the test house, there were secondary airflows between rooms that contributed to pollutant transport. These airflows were qualitatively estimated using neutral density soap bubbles. The bubbles followed the airflow in a room and between rooms. The bubbles showed that, even with the HVAC fan on, there was significant airflow directly between rooms with no mixing in the hall and between rooms and the hall with mixing in the hall.

Airflows between the closet in the corner bedroom and the bedroom were observed with the bubbles and were measured with a hot wire anemometer. These airflows were important for the moth crystal and dry-cleaning studies because the pollutant source was located in the closet.

Additional experiments to further characterize the airflows in the test house are planned.

Whenever possible, airflows should be determined by direct observation instead of via tracer gas measurements. The use of tracer gas measurements introduces circular logic into the model verification process. When tracer gas measurements are made, a model similar to the model being verified is used to estimate the airflows from the tracer concentration measurements. Then these airflows are used in a model to estimate pollutant concentrations. Even though the models are not identical, the basic assumptions used in the various models are essentially the same.

Additional house characterization tests were conducted and are reported by Jackson et al. (1987).

Moth Crystal Experiments

For the moth crystal experiments, the moth crystal cakes were placed in the closet of the corner bedroom (Clayton et al. 1988). The closet door was closed and the fan for the air-conditioning system was run continuously. The source term for use in the model was determined in small chamber studies (Nelms et al. 1987). The sink rate term was 0.3 $m/h/m^2$. The sink did not reemit. Measurements of p-dichlorobenzene concentration were made in the closet, the corner bedroom, the master bedroom, and the den. SF_6 measurements showed that the air exchange with the outdoors was 0.35 ach. The sink strength was estimated as discussed in the section on sinks. The results of the comparison between model predictions and experimental data are shown in Table 2. The agreement is very good.

As noted above, the model runs were made for a non-emitting sink. Measurements of the p-dichlorobenzene concentration in the test house after the moth crystals were removed from the closet showed that the sink did emit. Estimates of the sink emission term showed that the emission

TABLE 3

Comparison of Measured and Predicted Particulate Concentration from Kerosene Heaters.

Heater	Location	Predicted ug/m³	Measured ug/m
Convective	Den	60	68
Radiant	Master bedroom	52	36
Radiant	Den	285	279
Radiant	Master bedroom	235	242

rate from the sink was much less than the sink collection rate as long as the moth crystal source was in the house. However, the sink emission rate was high enough to maintain p-dichlorobenzene concentrations near 1 mg/m³ for several days after the moth crystals were removed.

Kerosene Heater Experiments

For the kerosene heater experiments, the heater was placed in the den. The heater was operated with a window open 5 cm. The particulate emission factors for use in the model were determined from large chamber studies. Particulate measurements were made in the den, the master bedroom, and the corner bedroom. SF_6 measurements showed that the air exchange with the outside was 0.4 ach. The sink strength was based on deposition velocities for small particles calculated from Fuchs (1964). The comparison between measurements and experiments is shown in Table 3. The experimental data for the kerosene heater experiments are reported in Jackson et al. (1988).

Dry Cleaning

For the dry-cleaning experiments, a standard load of dry cleaning was placed in the closet of the corner bedroom. The HVAC was allowed to operate normally (i.e., in an on/off cycle determined by the need for air conditioning). The source term for the dry-cleaning experiment was determined from small chamber experiments. The source term is plotted in Figure 3. A preliminary experiment was conducted to provide an estimate of the sink effect for the perchloroethylene. The sink experiment indicated that the sink was re-emitting.

Because the source term was not steady and the sink was re-emitting, the dry-cleaning experiment provided a more complicated test of the model than did the moth crystal and kerosene heater tests. The results of the comparison between the model and experimental data are shown in Figure 4 (taken from Tichenor et al. 1988).

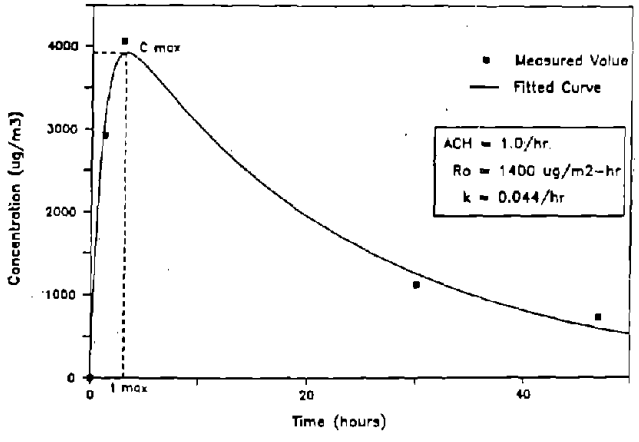

Figure 3 Perchlorethylene emissions from dry cleaning (modeling of small chamber data)

TABLE 4

Analysis of IAQ Control Options

Option	Pollutant Concentration, µg/m³ Room 1	Other rooms
Baseline	4166	1666
60% outside air in HVAC	3333	833
100% outside air in HVAC	3000	500
50% efficient air cleaner	3000	500
70% efficient air cleaner	2650	150
100% efficient air cleaner	2500	0
200 m³/h local ventilation	2267	900
400 m³/h local ventilation	1600	635
50% source reduction	2080	832
90% source reduction	420	170

Source of 1000 mg/h is in Room 1. The desired concentrations are 500 µg/m³ in Room 1 and 250 µg/m³ in all other rooms.

The model predictions are in good agreement with the experimental data for these three experiments. Additional experiments for model verification are planned with emphasis on aerosol spray products on wet sources. Additional experiments are also planned to better define room-to-room airflows and sink effects.

USES

The model has a wide range of uses, including helping with the global design of buildings, analyzing existing IAQ problems, estimating exposure to indoor pollutants, and analyzing IAQ control options. The use of the model to analyze IAQ control options is demonstrated below.

The model can be used to rapidly analyze the effectiveness of various IAQ control options. The model permits elimination of ineffective options and concentrates on the more effective options. As an example of this application, consider a five-room building with a strong source in one room. The allowable pollutant concentration in the room with the source is 1000 µg/m³ and the allowable concentration in the other rooms is 250 µg/m³. The data for the example are: all rooms are identical with a volume of 100 m³; all airflow is through the HVAC, which provides 400 m³/h into each room (30% of which is outdoor air); the source strength is 1000 mg/h;

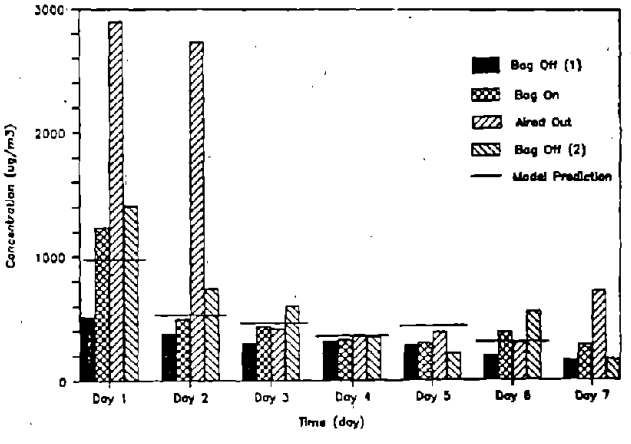

Figure 4 Perchlorethylene concentrations in closet from Tichenor et al. (1988)

there are no sinks: and the source is in room 1. The IAQ control options to be evaluated are:

1. Increase outside air to HVAC to 60% and 100%.
2. Allow local air exchange of 200 and 400 m^3/h in Room 1.
3. Use air cleaner with 50%, 70%, and 100% single-pass efficiency.
4. Reduce source strength by 50% and 90%.

The results of the model runs are shown in Table 4. Note that the only option that meets the concentration requirements for all rooms is the 90% source reduction. The air cleaner can meet the concentration requirements for all rooms except Room 1. The ventilation options do not meet the requirements for any of the rooms.

This example points out the importance of controlling the source and the general ineffectiveness of increasing general ventilation. The example also demonstrates that air cleaners can be effective in limiting the dispersion of pollutants through the HVAC system.

CONCLUSIONS

INDOOR is an easy-to-use tool for estimating pollutant distribution in a building. The model is in good agreement with experimental data. Additional research is needed to develop a library of default values of model input parameters. These defaults include source terms, sink terms, and room-to-room airflows under a wide range of conditions. Considerable additional work is also needed to better integrate exposure estimation with the overall model. At present, exposure must be estimated as a separate process.

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DEPOSITION OF NITROGEN DIOXIDE TO POROUS BIOLOGICAL SURFACES

Marc L. Bonem **Peter A. Scheff**

ABSTRACT

For this study, a completely stirred tank reactor (CSTR) was constructed and used to study the deposition of NO_2 onto plant and soil surfaces. Spider plants were chosen for study because they are a common house plant and NO_2 was chosen because it is an indoor air pollutant of major importance. Four separate surfaces were tested in this project: the polyethylene surface of the reactor chamber, empty clay pots, pots with soil, and spider plants (with and without exposure of the pots and soil). Deposition to all of the surfaces was clearly observed. With chamber, pot, soil, and plant surfaces exposed, the inlet concentration of 0.54 ppm was reduced to 0.16 ppm. Based on linear relationships between concentration and deposition, the estimated deposition for the experiment with pots, soil, and plants was within 15% of the measured total. Evaluation of the results showed that the data were better explained by a non-linear model. For the run with the pots, soil, and plants, it was found that the predicted deposition based on the non-linear model was within 5% of the measured deposition. A computer simulation was used to determine if plants can be a significant mechanism to remove NO_2 from indoor air; however, it was found that the plants will not make a significant difference in indoor concentration.

INTRODUCTION

The problem of indoor air pollution can be traced to two main causes. First, people spend most of their time indoors. Second, indoor air can be more polluted than outdoor air, in some cases exceeding federal standards. Sources of indoor air pollutants can include outside air infiltrating in; the earth; building and furniture materials; and combustion appliances like kerosene heaters or gas stoves (Wadden and Scheff 1983). Some plants can take in air pollutants and metabolize them. For example, bean plants were shown to take in NO_2 through the stomata in the leaves, and then reduce the NO_2 to NH_4, which could then be used as a nutrient (Rogers et al. 1979).

For this study, a completely stirred tank reactor (CSTR) was constructed and used to study the deposition of NO_2 onto plant and soil surfaces. The objectives were to:

1. Confirm the completely stirred tank reactor as an effective method to measure sink rates;
2. Develop rates of pollutant uptake by a plant and soil; and
3. Determine if plants are a significant sink for indoor air pollutants.

Spider plants were chosen for study because they are a common house plant and have been used in similar studies (Wolverton et al. 1984). NO_2 was chosen for study because it is an indoor air pollutant of major importance, it is easy to produce and measure, and it is known that plants metabolize NO_2.

EXPERIMENTAL

CSTR Model

Batch reactors have been commonly used to measure source and sink rates of pollutants to and from materials. This method has several problems. The concentration of pollutants is not necessarily uniform throughout the reactor. Because of this, the measured concentration may not be the same as the concentration at the surface. Monitoring the concentration may disturb the system. Finally, it may be difficult to make accurate measurements from small sample volumes removed from a batch system.

The CSTR overcomes these problems. The CSTR (Figure 1) consists of a chamber with an input and output. A propeller or impeller is used to mix the fluid in the chamber. Within the chamber, there can be a reaction, in this case, a source or sink of pollutant gas. For a CSTR, the outlet concentration is equal to the chamber concentration. The mathematical representation of the CSTR is:

$$V\frac{dC}{dt} = Q\,C_o - Q\,C + S - R \qquad (1)$$

where V is the chamber volume (m^3); C is the chamber or outlet concentration ($\mu g/m^3$); C_o is the inlet concentration ($\mu g/m^3$); S is the source rate ($\mu g/min$); R is the sink rate ($\mu g/min$); and t is time (min). The sink rate has been modeled as a first-order function of concentration (Wadden and Scheff 1983):

$$R = K_{dep}\,A\,C \qquad (2)$$

where K_{dep} is the deposition velocity (m/min) and A is the surface area (m^2). The linear constant K_{dep} is what characterizes the deposition of a pollutant to a surface and, because it has dimensions of rate of decay of NO_2 ($\mu g/m^2 \cdot min$) per mean concentration of NO_2 at the surface ($\mu g/m^3$), it is referred to as a deposition velocity.

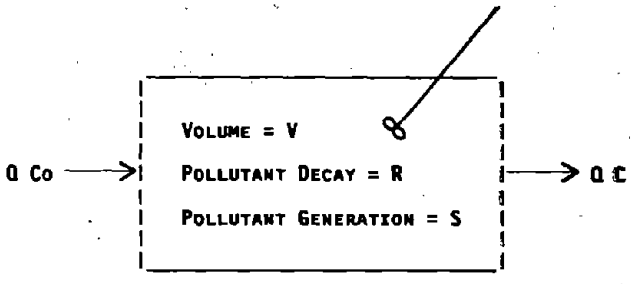

Figure 1 The completely stirred tank reactor

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Apparatus

The NO_2 was purchased from an industrial supply house. The gas was fed to a metering device which regulated the NO_2 flow and mixed it with filtered, dried air. Ambient NO and NO_2 were removed by the filtration system. The metering device fed the chamber inlet. The relative humidity of the air entering the chamber was 45%. The chamber was a polyethylene cylinder with a diameter of 55.7 cm, a height of 54.0 cm, and a total volume of 143.3 L. Polyethylene has been shown not to be a large sink for NO_2 (Spicer et al. 1986). Note that the later measurements were made in a batch reactor. Total flow through the chamber was 7.03 L/min, for a residence time of 20.4 min. The gas was mixed by an impeller turning at 370 rpm. Three 2.2-in-wide baffles at 120° created turbulence for better mixing. A 15-W fluorescent light provided 85 ± 13 footcandles (fc) of light at the base. The chamber is illustrated in Figure 2. Materials are inserted or removed by raising the chamber over the base. A mixing test was performed using a tracer gas and the system was found to be completely mixed (Bonem 1988). The chamber outlet was connected to an NO_2 analyzer, which used the chemiluminescent method to determine NO_x and NO concentrations. The output was recorded on a strip chart recorder.

Test Design

Four separate surfaces were tested in this project. The empty chamber was tested to characterize the deposition to the polyethylene surface. Empty clay pots were tested to characterize the deposition to the surface of the pots (correcting for the deposition to the chamber). Pots with soil were tested to characterize the deposition to the soil (correcting for removal by the chamber and pot surfaces). Plants were tested, with the pots and soil covered by plastic bags, to characterize the deposition to the plants. Finally, the plants were tested with the pots and soil exposed. This last test served as a check to see if the deposition of the sum of the surfaces would add up to the total deposition.

In each test, the concentration was raised and lowered in steps. Starting with zero concentration of NO_2, the concentration was raised to 0.25 ppm (463 $\mu g/m^3$) for six hours, 0.54 ppm (1003 $\mu g/m^3$) for six hours, down to 0.25 ppm for six hours, and back to zero for six hours. These levels were chosen to bracket typical acute values for a house with combustion sources (Wadden and Scheff 1983). Before each test, a calibration check was made using 0.4 ppm NO in N_2 calibration gas.

RESULTS

A graph of the inlet and outlet concentrations appears in Figure 3. Several things can be learned by a qualitative examination of this graph. It is clear that there is deposition to all surfaces. With chamber, pot, soil, and plant surfaces exposed, the inlet concentration of 0.54 ppm was reduced to 0.16 ppm.

There is also significant hysteresis in the system. The deposition at the first 0.25 ppm level (going up) is larger than the deposition at the second 0.25 ppm input (coming down). This might be explained by various parts of the system initially absorbing the NO_2 and desorbing the gas as the inlet concentration was decreased.

The figure also shows that with a 0.54 ppm input to the chamber, the uptake by the plants diminishes with time. This might be due to the toxic effects of the NO_2. The plants seem to recover after the concentration was reduced.

Linear Model

To determine the deposition velocities, several calculation steps were necessary, as illustrated in Table 1. The concentrations multiplied by the total gas flow rates gives the NO_2 mass flow rates. The total deposition or sink rates are then the difference between NO_2 mass flow into the chamber and the NO_2 mass flow out of the chamber. In the first experiment, the chamber is the only surface, so the total deposition is equal to the deposition to the chamber.

To separate the depositions to the other surfaces, it is necessary to use the relationship between deposition and concentration. For example, the deposition to the chamber is known only at the measured concentrations from the chamber-only experiment. However, there is deposition to the chamber at all other concentrations as well. Recall that as a surface was added, the chamber concentration decreased.

A linear model was developed from the empty chamber experiment and was used to determine the deposition to the chamber at all other concentrations. Thus, to determine the deposition to the pots, the deposition to the chamber is determined for the actual chamber concentration by the linear model, and the deposition to the pots calculated as the difference between the total deposition and deposition to the

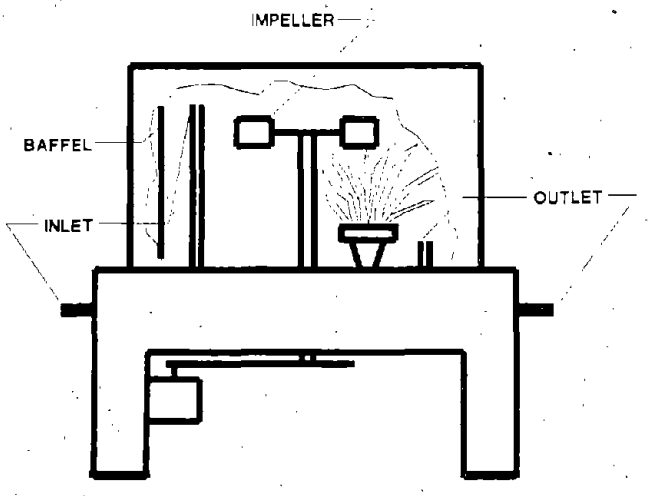

Figure 2 The chamber.

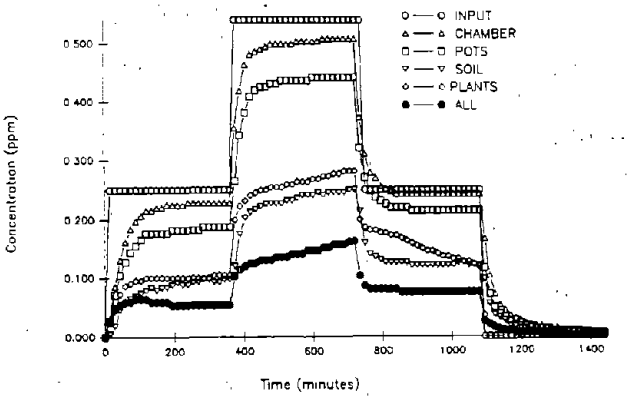

Figure 3 Concentrations with surfaces

TABLE 1

Concentration, Mass Flow and Deposition Rates

Test	Conc.[a]		Mass Flow[b]		Deposition, µg/min				
	in	out	in	out	total	chamber	pot	soil	plant
Chamber	469	425	3.30	2.99	0.307	0.307			
	1003	942	7.06	6.63	0.429	0.429			
	475	450	3.34	3.16					
Pot	462	358	3.25	3.52	0.733	0.283	0.477		
	1011	829	7.10	5.83	1.270	0.406	0.864		
	475	389	3.35	2.74					
Soil[c]	469	172	3.30	1.21	2.084	0.210	0.153	1.721	
	1009	464	7.11	3.26	3.840	0.319	0.333	3.188	
	469	231	3.30	1.63					
Plant	475	194	3.34	1.36	1.979	0.221	—	—	1.758
	1009	464	7.11	3.26	3.840	0.319	—	—	2.984
	469	231	3.30	1.63					
All	475	100	3.34	0.70	2.637	0.167	0.105	1.228	1.214
	1003	301	7.06	2.12	4.942	0.265	0.249	2.435	2.163
	475	150	3.35	1.06					
Soil[d]	313	118	2.02	0.83	1.371	0.180	0.114	1.077	
	503	207	3.54	1.45	2.081	0.227	0.177	1.677	
	767	352	5.40	2.48	2.917	0.284	0.268	2.365	
	1043	533	7.34	3.75	3.586	0.337	0.372	2.877	

[a]Concentration in µg/m^3.

[b]Mass flow rate in µg/min.

[c]Sunshine Aggrate Plus, Fissons Western Corp, Vancover, BC.

[d]Hyponex Professional Mix, Hyponex Corp., Atlanta, GA.

TABLE 2

Linear Model Deposition Velocities

Surface	Area, cm^2	Concentration, ppm		K_{dep}, cm/min
		Inlet	Outlet	
Chamber	15,443	0.25	0.23	0.0468
		0.54	0.51	0.0295
Pot	2004	0.25	0.19	0.615
		0.54	0.45	0.522
Soil	265	0.25	0.09	36.6
		0.54	0.25	26.0
Plant	2406	0.25	0.10	3.70
		0.54	0.29	2.34

chamber. A linear model for the deposition to the pots was then developed to be used for subsequent calculations. In this way, the deposition to each surface was modeled.

The deposition velocity was then calculated by dividing the deposition to each surface (sink rate) by the concentration and the area of the exposed surface. The deposition velocities are presented in Table 2. The surface area of the plants represents the total area of one side of the leaves. Based on the linear relationships between concentration and deposition, the sum of estimated depositions to the four surfaces for the experiment with pots, soil, and plants was within 15% of the measured total.

Non-Linear Model

When the data points for each surface are plotted with the linear models, the lines do not pass through the origin (Figure 4). This is physically impossible, as the deposition

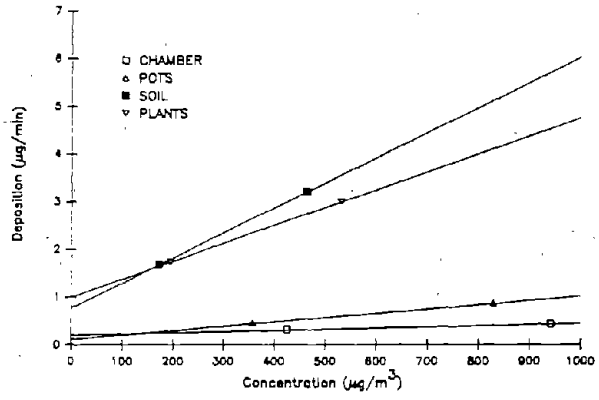

Figure 4 Data and linear models

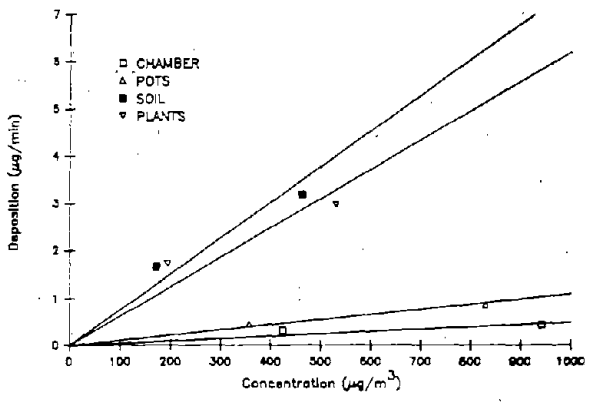

Figure 5 Data and linear models through zero

TABLE 3

Non-Linear Model Deposition Constants

Surface	Area, cm^2	K_{nl}	n
Chamber	15,443	0.0160	0.417
Pot	2004	0.0220	0.786
Soil	265	2.63	0.623
Plant	2406	0.458	0.525

must be zero for a zero chamber concentration. This observation calls the linear model into question. If least-squares linear models are constructed that force the line through the origin, it is seen that the data vary from the model in a consistent manner (Figure 5). The data are above the model at lower chamber concentrations, and below the model at higher chamber concentrations. These observations suggest that a non-linear model of concentration and deposition may be required. A non-linear model using the following parabolic relationship was used to model the deposition rate:

$$R = K_{nl} C^n \quad (3)$$

where K_{nl} and n are fitted parameters. A new constant, K_{nl} (non-linear), is used because the constant is no longer a deposition velocity. Table 3 summarizes the results of calculations based on the parabolic model. For the run with the pots, soil, and plants, it was found that the agreement between the sum of the predicted deposition to the surfaces and the measured deposition to all of the surfaces was now within 5% for both inlet concentrations. This demonstrates the validity of the non-linear model and the effectiveness of the CSTR as a tool to develop sink rates.

Because non-linear deposition is a departure from previous work, it was felt that another test with more data points should be run to confirm the result. A test with a second soil using four steps up in concentration was made. Figure 6 shows the data points graphed with the fitted parabolic model. The r^2 for the curve is 0.999.

An unexplained phenomenon occurred during the soil tests. The soil covered NO_2 to large amounts of what appears to be NO. This is significant since NO is less toxic than NO_2. Another soil was tested with similar results. A sample of soil was sterilized with gamma radiation to determine if the reaction was biological in origin. The sterile soil, however, also generated the NO. Nishimura et al. (1986) reported conversion of NO_2 to NO by some plants. Spicer et al. (1986) and Yamanaka (1984) report similar reactions with building materials. Pitts et al. (1985) found nitrous acid (HONO) to be a decay product of NO_2. Either NO_2 is being chemically converted to NO, or NO_2 is being converted to HONO and is interpreted by the chemiluminescent reaction in the NO_x analyzer as NO.

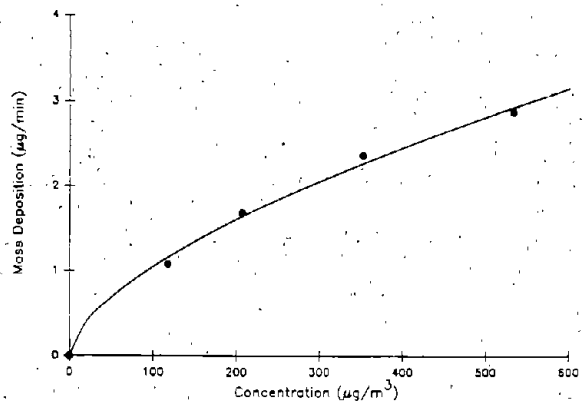

Figure 6 Deposition vs. concentration for soil

Application

A computer simulation was used to determine if plants can be a significant mechanism to remove NO_2 from indoor air. The SIMBAS program, by H.R. Bungay and modified by C.N. Haas, solves differential equations over time. A living room with furniture and four spider plants was simulated using the deposition constants developed in this experiment. The plant deposition velocity was 0.0369 m/min (0.121 ft/min), the soil deposition velocity was 0.3361 m/min (1.102 ft/min), and the room deposition velocity was 0.0054 m/min (0.0177 ft/min) (Wadden and Scheff 1983). The room volume was 762.4 m^3 (2500 ft^3), and the airflow rate was 12.71 m^3/min (1 ach). As illustrated in Figure 7, the plants do not make a significant difference. Another simulation, using 10 plants, is illustrated in Figure 8. Though the deposition is now observable, it is still not significant.

CONCLUSION

The CSTR is an effective tool to measure indoor pollutant source and sink rates. Plants and soil take up NO_2; however, the surface area is likely to be too small to be significant in an indoor environment. We also observed that when analyzed by a chemiluminescence analyzer, soil transforms NO_2 into another gas which appears to be NO. Our

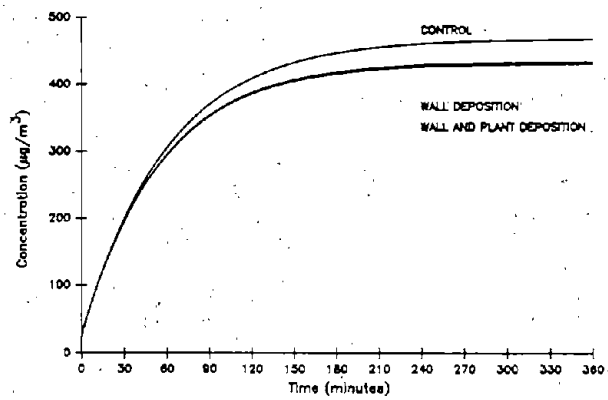

Figure 7 Room simulation with four plants

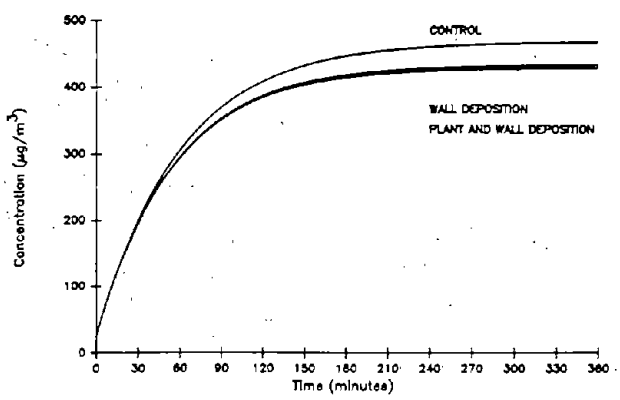

Figure 8 Room simulation with ten plants

data suggest that the assumption of a linear relationship between concentration and deposition is not correct. For our data, a parabolic model more accurately represents this relationship.

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FORMALDEHYDE EMISSIONS FROM BONDED FIBERGLASS INSULATION PRODUCTS

P.F. Miele

ABSTRACT

In recent years there has been much concern about the quality of air we breathe inside our homes, schools, and workplaces. The presence of formaldehyde in indoor air has been suspected as the cause of many irritant reactions associated with "sick building syndrome." Although fiberglass duct liner, duct board, and other building insulation products are bonded with phenol-formaldehyde-urea adhesives, literature references show that bonded fiberglass products are low emitters of formaldehyde.

The purpose of this study was the investigation of the formaldehyde emissions from bonded fiberglass products using the large-scale test chamber methodology. The test evaluation is similar to what is specified in HUD ruling 3280.308, "LSTC Method of Determining Formaldehyde Emissions from Wood Products FTM-2-1983," which went into effect February 11, 1985.

Employing standard test conditions of 50% RH, 77°F, and 0.5 air changes per hour (ach), fiberglass air-handling and insulation products emitted 100 parts per billion (ppb) or less of formaldehyde when test chamber loadings approximated the installed ratio of product area to indoor air space volume.

INTRODUCTION

Formaldehyde-based resins are used extensively as the bonding agent in many construction materials. Bonded fiberglass insulation products are typically manufactured with phenol-formaldehyde-urea adhesives at levels up to 20% of product weight.

Although research has shown phenol-formaldehyde-urea adhesives to be low emitters of formaldehyde (CPSC 1983) it is incumbent on manufacturers to achieve the lowest possible formaldehyde off-gassing from products in view of the varied human responses to formaldehyde vapor at levels of 0.5 ppm or less (NRC 1981).

Data on the formaldehyde off-gassing of bonded fiberglass insulation products are limited compared to pressed wood products.

Since a dynamic (ventilated) test chamber more closely duplicates actual product use than does a test apparatus with no ventilation, the products tested in this study were evaluated in a large-scale test chamber (LSTC). The LSTC (NPA/HPMA 1983) method determines the dynamic state formaldehyde emission potential of products under conditions that simulate ambient indoor air. The emission potential is determined by measuring formaldehyde chamber concentrations under defined test conditions. The Hardwood-Plywood Manufacturers Association provides test apparatus and method protocol in its test method, FTM-2-1983, "Large Scale Test Method for Determining Formaldehyde Emissions from Wood Products." The U.S. Department of Housing and Urban Development (HUD) adopted FTM-2-1983 in 1985 when it established the world's first government formaldehyde standards for pressed-wood products used in mobile homes (HUD 1984). The HUD ruling states that certain pressed wood products cannot exceed formaldehyde chamber concentrations at specific product loadings. Thus the use of an LSTC, which utilizes standard conditions of temperature, humidity, ventilation, and product loading, has emerged as one of the important test methods for evaluating the formaldehyde emission potential of various building materials.

In this study commercial and residential fiberglass insulation products were selected for testing as well as some fiberglass products used in HVAC systems.

A test chamber loading of 0.52 m^2/m^3 (0.16 ft^2/ft^3) was used for batt and roll fiberglass insulation products based on an outside wall insulation area of a one-story structure. Chamber loading values for fiberglass duct board (0.07 m^2/m^3) and duct liner (0.12 m^2/m^3) were based on the installed area of the air-handling product in a residential structure. Conditioning time, or time to equilibration of formaldehyde release, was determined to be 24 hours or less for the fiberglass samples. The fiberglass batt and roll insulation products were all tested at 77°F and 50% RH. The two air-handling products were tested at higher temperatures (lower relative humidity), in addition to ambient temperature, to approximate service conditions. All samples used in the study were manufactured at least one month prior to securement.

TEST METHOD

The bonded fiberglass samples were evaluated in Georgia-Pacific's 1077 ft^3 (30.5 m^3) large-scale chamber located in Sacramento, CA (Newton et al. 1986). The test chamber is constructed of embossed aluminum panels that are filled with an insulating styrofoam and interfaced with each other using an epoxy adhesive. The chamber dimensions are 16.72 ft long, 9 ft high, and 7.15 ft wide. A variable-speed blower pumps air to the test chamber from a conditioning room where temperature and relative humidity are controlled to 77°F ± 2°F and 50% ± 4% RH, respectively. The air in the conditioning room is scrubbed with a bed of chemisorbent to reduce formaldehyde levels to less than 5 ppb. The air passes through a positive displacement gas meter for volume measurement prior to entering the chamber through a rigid, non-metallic conduit. The air is diffused into the chamber through numerous holes while a three-speed fan with a plastic baffle aids in chamber air circulation. The air exchange rate was controlled to 0.50 ± .05 ach.

The fiberglass samples, which represented faced and unfaced material, were placed on metal support racks within the chamber so that the facing and fiber side of the fiberglass samples were equally exposed to the chamber environmental conditions. Temperature, humidity, and air exchange rate within the chamber were allowed to equilibrate for 24 hours prior to each test. A background chamber value was determined before placing test samples in the chamber. Once in

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TABLE 1

Large Scale Test Chamber Results

Product	Temp. °F	RH %	Chamber Loading m^2/m^3	ACH	Chamber Background Formaldehyde ppm	Chamber Formaldehyde ppm
R-30, 11.5 "(a)	77	50	0.52	0.50	0.024	0.065
R-19, 6.5"(a)	77	50	0.52	0.50	0.026	0.072
R-11, 3.5"(a)	77	50	0.52	0.50	0.025	0.072
R-11, 3.5" UNF	77	50	0.52	0.50	0.028	0.085
R-13, 4", UNF	77	50	0.52	0.50	0.028	0.085
Duct Liner, 1"(b)	77	50	0.12	0.50	0.028	0.015
Duct Liner, 1"(b)	110	10	0.12	0.50	0.026	0.020
Duct Board, 1"(c)	77	50	0.07	0.50	0.026	0.028
Duct Board, 1"(c)	110	10	0.07	0.50	0.027	0.051
Duct Board, 1"(c)	110	10	0.07	0.50	0.026	0.070

(a) Kraft faced building insulation
(b) Nonwoven fabric facing
(c) Foil scrim kraft facing

the chamber, test samples were equilibrated for 24 hours before sampling the chamber air for formaldehyde. The modified NIOSH test procedure was the analytical method used to determine the formaldehyde. The modified NIOSH method uses 1% sodium bisulfite as the absorbing solution in two series-connected impingers each containing 20 ml of absorbing solution. The air sample was taken over a one-hour period at a sample flow rate of 1 L/min. The measured formaldehyde was reported as parts per million (ppm) in the sampled chamber air.

RESULTS

The results of the large-scale chamber testing at 77°F, 50% RH, and 110°F, 10% RH with 0.50 ach are summarized in Table 1. The steady-state formaldehyde concentrations (C_s), or chamber formaldehyde values, varied from 0.015 ppm to 0.085 ppm for the tested samples. Since little variation was observed in the chamber values (C_s) for the residential insulation product, it would appear that the formaldehyde emission levels are dependent on product surface area and not product thickness or weight. Chamber values for the duct liner samples were below the chamber background levels, indicating that these samples acted as a sink adsorbing formaldehyde. The duct board results at 77°F and 50% RH show formaldehyde values the same as chamber background. With increasing test temperatures (110°F and 120°F) and lower relative humidity, the chamber formaldehyde values increased to levels above background readings.

Although humidity has been shown to affect the formaldehyde off-gassing of bonded wood products, it is not known what effect HVAC cooling conditions (55°F, 95% RH) would have on formaldehyde off-gassing of fiberglass products.

CONCLUSIONS

A large-scale test chamber with a modified FTM-2-1983 wood products protocol was used to measure formaldehyde emissions from bonded fiberglass products. At chamber conditions of 77°F, 50% RH, and 0.50 ach, the measured formaldehyde values were 15 to 85 ppb. The measured formaldehyde emission values, employing approximate product end-use chamber loadings, are below the ASHRAE (1986) recommended guideline of 100 ppb.

Since many of the large chamber test values are very close to the chamber background formaldehyde values, the formaldehyde contribution of the fiberglass products is not being accurately determined. Therefore, it is not feasible to use the test results to calculate an accurate emission rate (mg/m^2/h).

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IAQPC: AN INDOOR AIR QUALITY SIMULATOR

M.K. Owen P.A. Lawless T. Yamamoto D.S. Ensor L.E. Sparks

ABSTRACT

An Indoor Air Quality Simulator for Personal Computers (IAQPC) has been developed in response to the growing need for quick, accurate predictions of indoor air contamination levels. Heating, ventilating, and air-conditioning (HVAC) system designers need ways to determine if a planned system will ensure the health of building occupants. Scientists will find this program useful as an experimental design aid. Building maintenance personnel will be able to use it to determine approaches that will alleviate contamination problems.

Version 2 of the Indoor Air Quality Simulator has been developed at a research institute under a cooperative agreement with the U.S. Environmental Protection Agency. This program extends Version 1 with more extensive input menus and output options. Improved algorithms for contaminant transport and flow have been incorporated. The program runs in a fraction of the time necessary for other current models.

This program models up to six pollutants concurrently for buildings of up to 20 rooms. It allows inclusion of sources, sinks, and air cleaners and can be adapted to a wide range of structures. The algorithms used to determine the concentrations have been tested against experimental data and found to yield accurate predictions. This paper describes the model's inputs, calculations, and outputs and presents a case study performed with the model.

INTRODUCTION

As the awareness of the potential health and air quality control problems resulting from indoor air contamination has increased, research has begun to determine the concentrations of pollutants in indoor air. Many potential sources have been studied in experimental studies; some have been studied in actual buildings. Work has begun in testing air-cleaning devices both in laboratories and in buildings. Some studies have been done to determine actual contaminant levels in occupied spaces. However, for this information to be used by building designers, HVAC system operators, and occupants, an easy-to-use, readily accessible, and quick method is necessary to disseminate the information and to apply the relevant data to any given situation. IAQPC is one answer to these needs.

IAQPC is an indoor air quality simulator for use on personal computers. Menus are used to enter data, describe the specific building, run the program, and output the results. This edition of the model, Version 2, has been developed at a research institute under a cooperative agreement with the U.S. Environmental Protection Agency. This program extends Version 1 (Sparks et al. 1988) with more extensive input menus and output options. Improved, faster algorithms for contaminant transport and flow have been incorporated. The algorithms that are used in this program run approximately 10 times as fast as the CONTAM program developed by the National Bureau of Standards (now the National Institute of Standards and Technology) (CONTAM 1987).

DESCRIPTION OF THE PROGRAM

This program is easy to use in spite of the multiplicity of inputs required. Menus provide easy access to data input, run program, and output options. The main menu (Figure 1) gives the user access to the data entry, calculation, and data output options of this program. This approach makes it simple to enter the basic building design, HVAC system design, pollutant descriptions, and the source and sink locations (a sink is anything that removes a pollutant from the air).

Through the basic design menu (Figure 2) the user specifies the building floor plan, room volumes, and interconnections. This model is for use with any single-story building with an HVAC system. The floor plan to simulate the structure need not match the actual layout. The important consideration is to match function.

There are six possible basic layouts for the building, as shown in Figure 3. Each has a minimum number of rooms and expansion rooms. The total number of rooms may range from 2 to 20. The interconnections between the rooms, outside, and the HVAC system are specified as total connecting areas. These areas provide a relative measure of flow resistance and are not necessarily equal to the physical area. For example, if a room has an open 3 ft by 8 ft door connecting to the hall, the approximate hall interconnection value will be 24. If the door is to be shut during the run, a small value for the crack under the door, possibly 0.25 (for 1 in by 3 ft), would be specified. A summary of the room volumes and connecting areas for all the rooms in the building can be viewed in a convenient table in a window that opens up on the screen.

Values directly related to the HVAC system are entered in the HVAC system design menu. Required data include the total flow when the system is on, flow when the HVAC system is off, pressure head, and fraction of makeup air. A sub-menu allows selection of up to eight on/off changes in the HVAC system status for every 24 hours of simulated time. The HVAC system is assumed to be off until the first time specified.

Several options, besides data input, are available through this menu. The airflows may be balanced and displayed while in this menu, allowing the user to check the values before running the simulator. This is especially useful if a building has been experimentally characterized. The user may check to see that the calculated values reflect the real values and change the input data, such as the interconnecting areas, to achieve precise results.

The pollutant characteristics menu allows the user to choose which pollutants will be modeled and to enter source rates, air cleaner efficiencies, concentration averaging periods, acceptable limits, and outdoor concentrations. From

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I N D O O R A I R Q U A L I T Y
S I M U L A T O R
Main Menu

Basic Building Design
HVAC System Description
Pollutant Characteristics
Air Cleaners/Sinks
In-Room Locations
Start Simulator
Continue Simulation
Graphical Output
Output Results
Runtime Configuration

Quit to Prior Menu <Esc>

Use the arrow keys to position the cursor.
Use <Enter> to select the option.

Figure 1 IAQPC's main menu

one to six pollutants may be modeled. There are 11 pollutant names to choose from including three sizes of particles, carbon dioxide, and volatile organic compounds (VOC). At this point, however, there are no pollutant-specific calculations, so that any of the pollutant listings can be used to simulate any pollutant as long as the corresponding source and sink terms are correct. Source rates for many common pollutant sources can be changed to reflect the actual rates, if known. For example, if a certain brand of cigarette is to be a source, the particulate production rate can be looked up and entered.

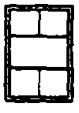
In a manner similar to that used for sources, sink rates can be specified. Four types of passive sinks may be included: horizontal, vertical, furniture, and people. Collection and reemission rates for the chosen pollutants may be input. The reemission rates allow the sinks to collect and reemit the pollutant. The reemission rate is a fraction of the total collected amount that will be given off in the given time interval.

The user may also choose which types of air cleaners are available and may specify the collection efficiencies for these devices. Up to two room type and two HVAC system cleaners may be selected. Efficiencies for the air cleaners for each pollutant may be specified.

Concentration limits and corresponding averaging periods are also input. These values enable the program to determine a suitable average concentration for each specified pollutant and to compare this with the appropriate limit. In this way, the user can be warned if concentrations will exceed threshold values or air quality standards. The default values

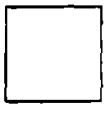
Expanded Floor Plan 3

Central Hall
4 rooms & hall



1 2
0
4 3

Hall Connecting Area (ft^2)
Outside



HVAC room inlet	.4
Outside wall(s)	.2
Next room	0
Prior room	0
Hall	0
HVAC room return	1

Quit <Esc>

B A S I C B U I L D I N G
D E S I G N

Floor Plan Selection	3
Number of Rooms	4
Room Number	0
Volume (ft^3)	200
Interconnections	
Upward Room# Copy	<F3>
Downward Room# Copy	<F4>
Building Statistics	
Load Building Design	
Save Building Design	

Quit to Main Meanu <Esc>

Use cursor keys to select option.
Use <Enter> to activate option.
Use →/← to change room number.

Figure 2 Basic design menu

are those for recognized standards. In addition, the concentration limits are used to normalize the output values before graphing.

Ambient concentrations of pollutants are also specified. The default values are considered to be typical of outdoor air, but some regions will need adjustment. These values may be used as the initial concentrations inside the building.

In addition to specifying source and sink rates, it is necessary to specify their locations. The in-room sources menu allows the choice of which generic sources are present in each room, the hall, and the HVAC system. The in-room sink menu allows the user to select the sinks present. The air cleaners present in any room or the hall are selected, as is the method the program uses to set the initial in-room concentrations (five options are available: zero all concentrations, ambient concentrations, HVAC system concentrations, local equilibrium, and initialize configuration). Again, a summary of the sources and sinks for the building is available as a window inset.

IAQPC allows the user to specify various runtime and menu use options. The runtime configuration options include the time increment to be used by the program. Allowable values are 0.1 to 2.0 hours in increments of 0.1 hour. The print step is the interval at which new values will be printed. The run duration is the length of time in days that the calculations will cover—currently up to 30 days.

The interrupt every (hr) instructs the program to stop calculations at regular intervals. When the program reaches this point, it prints a message to the screen asking the user to press any key to continue. This allows the user to examine the values, then continue or escape, change parameters, and resume calculations. For example, if the user wishes to determine the effect of opening and closing a window every two hours, the interrupt would be set to 2. Then the user would escape, change the outside connection area in the appropriate room, and continue the program.

The menu use options include the choice of highlighting the current choice (bar) or a blinking arrow in front of the choice. The key letter enable allows the user to press the first letter of a choice to select that choice, or the cursor can be moved by cursor keys or a mouse. Graphics display determines whether graphical output will be available. Setting this option to "off" lets the program run even if the computer does not have graphics capabilities. An on-line calculator is available simply by pressing <F9>. This makes it simple to convert units or calculate areas given dimensions.

The program running options are start simulator, which begins calculations, and continue simulation, which continues the simulation at the point where an interruption occurs. In both cases, the screen will clear, then plot the values as they are calculated. Figure 4 is an example of the graphical output that shows the concentrations of two pollutants over approximately 36 hours.

Output options include a table of the current concentrations, the flow rates as calculated for the building, and a summary of the input data.

TECHNICAL APPROACH

A fast direct solution method to describe a multizone indoor contaminant distribution was developed. It is assumed that mass is conserved or accounted for in the structure.

If the assumption is made that the neighboring concentrations and source terms do not change during the time step selected, then

$$C_i = C_i(t_o)exp(-L_i t) + P_i(1 - exp(-L_i t))/L_i \quad (1)$$

where

$C_i(t_o)$ = the concentration for room i at time $t = t_o$

L_i = loss rate of pollutants leaving room i per unit time

P_i = production rate of pollutants entering room i per unit time

The discrete solution method approaches the exact solution as the time step decreases. At any given starting time, the concentration for each room is known or set by the initial conditions. After the concentrations of all zones during the time step have been computed, the pollutant concentration for supply air is computed. The concentration in each room that has just been calculated is used as the initial concentration for the next time step. This procedure is repeated until the final time is reached. The order of calculation is not im-

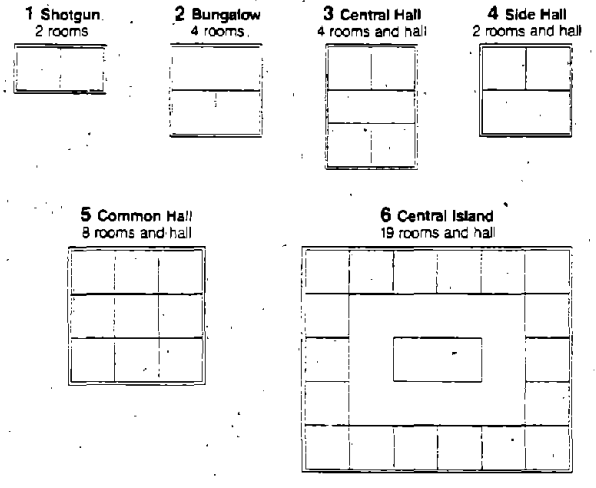


Figure 3 The six available building layouts

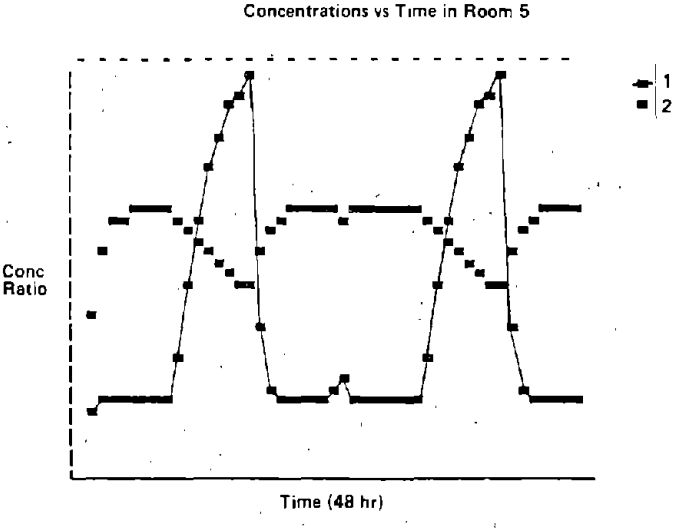


Figure 4 A sample of IAQPC's graphical output

portant. For a complete description of the algorithm, see Yamamoto et al. (1988).

To compare the execution time to run this program with that for the CONTAM model (a state-of-the-art program with extensive algorithms), identical cases were run with both programs. The comparison case, a 12-zone simulation of an office building, represented a building for which experimental data are available (Owen et al. 1986). The algorithm used in IAQPC, another algorithm also developed at this facility, and the CONTAM model were compared. All three gave results that were quite consistent with the experimental results; however, this algorithm ran approximately 10 times as fast as CONTAM (Yamamoto et al. 1988). It also runs much faster than Version 1.

The flow-balancing algorithm uses pressure-driven flows, with a strict pressure balance maintained for the system with "areas" used to represent the flow resistance. The mass flow error in each room is used to provide a relaxation correction to the pressure in the room. Convergence to mass balance in all rooms is the criterion for overall convergence.

DISCUSSION

IAQPC is a user-friendly program. The incorporation of simple-to-use, easy-to-understand menus into a contaminant calculation program enables any user to benefit from this program. Menu use options make it possible to tailor the menus to an individual. The program can be operated by mouse, with first letter control, with an arrow or a highlighted cursor, and in color or not. These options allows the user to individualize the program for ease in running.

A new user with basic knowledge of concentration levels and building design should have little trouble using the program. The program provides on-screen instructions and a user's manual—complete with tutorial and program flowchart. A user with no computer experience will need to be cautioned to save data files, turn on the printer, and other basic hints as would be needed for any program use. A user with spreadsheet experience will find this menu design fairly familiar; options are presented, then chosen as in a spreadsheet. A Version 1 user will merely need to become acquainted with the available options. All users should try the tutorial first, then proceed with experimentation. Any user should be able to set up a simple case and obtain results in less than an hour. More complicated cases will take longer to set up simply because of the data entry time. As the program is used, the user will learn more about it and become comfortable with the many options.

Building description is simplified by giving the user a choice of floor plans. The six available floor plans can be used to describe almost any building. This procedure sets up the connections between rooms without the necessity for the user to laboriously specify which room is connected to what. The chosen floor plan need not match the actual layout but should match in function.

Since the connections between rooms are specified by cross-sectional areas, any building may be characterized using only basic floor plans and a survey to determine which doors, etc., are open. It is not necessary to have experimental airflow data in order to determine airflows in the building. However, if detailed SF_6 or other flow rate data are available, the interconnecting areas can be specified, then refined to produce the actual flow rates. In addition, this approach makes it simple to determine the effect of changes in the building, such as the opening of a door or window. Again, the "area" may not correspond exactly to a physical area, but is a statement of the flow resistance. This program may also be used to check plausibility of experimental data. For example, it can verify that measured airflows and concentrations are consistent.

The HVAC data entry options that allow the user to specify total flow and percent makeup air make it possible to determine the effect of these two parameters on the indoor concentrations. These parameters are two of the most important for the system designer and the building HVAC operator. Since energy efficiency is directly related to the flow rate and, even more, to the percentage of outdoor air (which may have to be cooled, heated, or dehumidified), it is important to be able to determine minimum acceptable flows. With IAQPC, these values can be changed quickly and their effects studied. Also, sources can be changed to determine if lower flows would be acceptable if certain sources were eliminated, moved, or vented. In the same way, an experimenter can use these options to aid in experimental design. The results of computer runs will indicate what parameters will be influential and need actual study.

Since this program allows up to six pollutants to be modeled, much time can be saved over the separate runs required per pollutant in previous air quality programs. The generic sources (cigarette, heater, etc.) have default values that are standard for the particular source; this allows the user to specify sources without having to look up source strengths. However, when the user has emissions data for specific sources, these numbers can be input for source strength on final concentrations. For example, if a homeowner wished to decide between brands of heaters based on the resultant pollutant levels, this program would enable the prediction of levels based on the specific heater's byproducts.

In the same way, the possible sinks and air cleaners can be manipulated to determine, for example, the effect of more efficient filters or of removing a charcoal filter. Knowledge of the effect of various air-cleaning devices could benefit a designer by helping to determine the lowest pressure drop for a filter that will yield acceptable air conditions, therefore helping to size the building fans.

Since both the sources and sinks can be specified in any location or combination of locations, IAQPC is very versatile. Sources can be moved to determine, for example, the most reasonable location for the copy machine or how smokers should be placed to have the least impact on an office building as a whole.

The concentration limits, combined with the averaging periods, will make IAQPC a useful tool for building assessment when there is a possibility that air quality standards will be exceeded. This program will help the owner meet safety standards. Changing the concentration limits can be used to increase the comprehensibility of the output graph. If more than one curve occurs in the same region of the graph, the user can change one of the limits in order to shift that portion of the plot. The runtime output and program output options make it possible to obtain the required data in the most readily usable form.

All of the options, combined with the speed of IAQPC, make this program the ideal tool for many HVAC professionals and building occupants, as well as scientists investigating indoor air phenomena. This program and appropriate documentation will be available through normal EPA channels as soon as release approval has been obtained.

TABLE 1

HVAC System Airflows in Test House

Room	Measured Airflows (cfm)
Den	400
Middle Bedroom	165
Corner Bedroom	164
Master Bedroom	165

TABLE 2

Measured Concentrations in Test House (mg/m³)

Day/Room	Closet	Corner Bedroom	Master Bedroom	Den
1	107	4.72	3.49	3.84
2	53.6	4.41	3.50	3.30
3	70.9	5.51	4.18	3.80
4	63.0	5.61	4.27	4.02

TABLE 3

Interconnecting Areas (ft²) and Volumes (ft³) Floor Plan 4

Room	Volume	HVAC: In	Ret	Walls: Out	Nxt Rm	Pr Rm	Hall
0	457	0.00	5.00	0.00	0.00	0.00	0.00
1	1375	2.55	0.00	0.13	0.00	0.00	21.00
2	5468	6.70	0.00	0.29	0.00	0.00	34.40
3	1067	0.31	0.00	0.01	0.00	0.00	21.00
4	1124	2.55	0.00	0.13	0.32	0.00	21.00
5	99	0.04	0.00	0.00	0.00	0.32	0.00
Total	9590	12.15	5.00	0.56			

TABLE 4

Airflows (cfm)

Room	ACh/Hr	HV In	HV Ret	Outside	Nxt Rm	Pr Rm	Hall	Total
0	90.3	0	−688	0	0	0	688	−0
1	7.1	162	0	−14	0	0	−147	1
2	4.4	404	0	−32	0	0	−371	1
3	1.2	21	0	−1	0	0	−19	1
4	8.8	161	0	−14	3	0	−150	1
5	2.4	4	0	0	0	−30	−0	1
Total	3.7	752	−688	−61				

SAMPLE CASE

This sample case compares the output for IAQPC to experimental data for the EPA test house in Cary, NC. The actual data are briefly discussed. The procedure used to model the case and the input values are listed, then the results are compared. This serves to show the level of accuracy of the program and introduces some of the program options.

Description of Experiment

Flow rates were determined in the house when the ventilating system was on. The HVAC system was initially on and was left on for the duration of the test. Moth cakes—p-dichlorobenzene—were placed in one closet. Figure 5 shows the actual layout of the building. The p-dichlorobenzene emission rate was determined to be 1.4 mg/cm²·h. The area of the moth cakes was 570 cm². Airflows into the rooms from the HVAC system are given in Table 1. All airflow from the interior to the HVAC system is through the return ducts in the hall. The airflow between the closet and the bedroom was determined to be approximately 2.3 cfm. An infiltration rate of outdoor air of 0.35 air changes per hour was determined. Concentrations were determined in four locations for four days beginning three days after the cakes were positioned. These are shown in Table 2. For more details, see Sparks et al. (1988).

Modeling Procedure

In order to model this case, a floor plan had to be chosen. More than one of the plans could have been used. Since there were no data on flow or sources in many of the rooms, a five-room simulation was chosen. The floor plan shown in Figure 6 was used since there are no interconnections between the master bedroom and the closet. Note that room number 0 is the hall; room number 6 is the HVAC system.

The room volumes were determined directly from the floor plan, then entered into the program. Reasonable guesses were made for all of the interconnecting areas. For example, it was assumed that open doors would connect all the rooms, except the closet, to the hall. This resulted in the use of 21 ft² (3 ft by 7 ft) for the interconnection between the four main rooms and the hall. The outlet and return vents

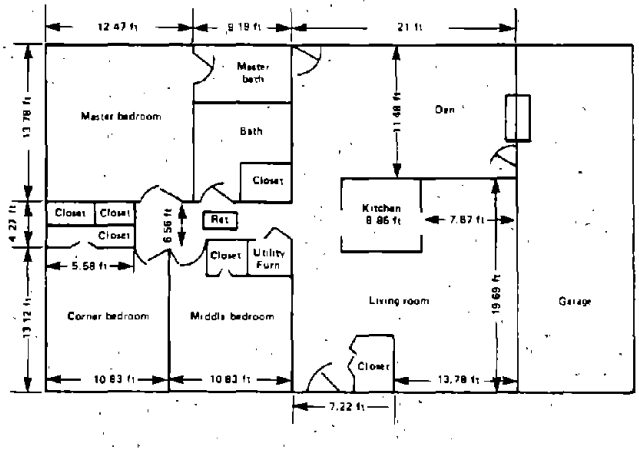


Figure 5 Floor plan of EPA IAQ test house

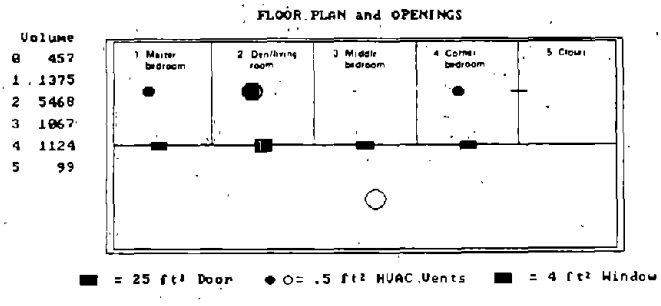


Figure 6 Layout for simulation of EPA test house

TABLE 5

Model Concentrations for Test House (mg/m³)

Closet	Corner Bedroom	Master Bedroom	Den
65.8	9.75	8.96	8.96

were assigned much smaller values. The door to the closet was assumed shut, so a small value was given to the area between the room and the closet. In order to force air through the closet, a value was given for an HVAC vent. Also, all four rooms with outside walls were given values to represent cracks or slightly open windows so that air could escape from the building (thus making outdoor air intake possible).

The total volume of the five rooms and the air exchange rate were used to determine the amount of outdoor air entering the building. The flows were added up and entered into the program as the total flow and fraction of outdoor air values. Then the airflows were balanced through the HVAC system design menu. The airflows were then examined and adjustments were made to the interconnecting areas so that the flow rates corresponded closely to the actual values. The final interconnecting areas, room volumes, and flow rates are shown in Tables 3 and 4.

Next, the pollutant choice menu was used to choose dichlorobenzene as the pollutant to be modeled. The generation rate of the generic source (mothcakes) was set as 79.8 mg per 0.1 hour. The appropriate runtime settings were specified: print output to screen, save data to file as generated, print time of 0.5 h, etc.

Then the simulator was run. The on-screen graphical output for the corner bedroom (room 4) is shown in Figure 7. The concentrations reached their final values in fewer than 24 hours so that one set of numbers covers the times for all of the readings. These values are shown in Table 5. In this case, the time to model four days was only 35 seconds.

The closest concentration is well within the range of the experimental values. The other three numbers are fairly close. Obviously, given the detail of the input data, the model does a good job of predicting the actual values.

This sample case shows some of the options and flexibility of IAQPC. It also shows that the calculated concentrations are a good reflection of the measured values.

CONCLUSIONS

1. IAQPC fills the current need for a quick, user-friendly method of determining potential indoor air problems. This model will allow both building users and designers to determine potential problem areas and IAQ control approaches.
2. Experimental design will be simplified with IAQPC. Variables such as flow rates, makeup air percentage, HVAC schedule, room configuration, sources, and source location that are most likely to influence pollutant concentrations can be determined. It is also possible to use IAQPC to determine if experimental data are plausible.
3. Experimental data verify that the program does predict actual values.
4. Further experimental data will enable the fine tuning of the program's calculation schemes, in particular, airflow resistance areas and source/sink values.

PLANNED DEVELOPMENTS

1. Experimental work to characterize indoor sources will be performed after using IAQPC to examine possible outcomes in order to design optimum experiments.
2. Data from experiments will be used to verify or modify the assumptions in the model.
3. Additional sink types and pollutant interactions will be included as these phenomena become better understood. Eventually a model that incorporates costs and health effects will be developed.

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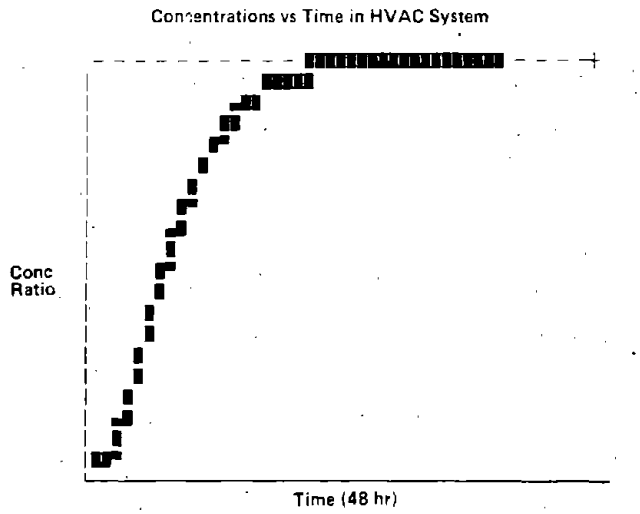

Figure 7 On-screen graphical output for corner bedroom

OBSERVED FORMALDEHYDE LEVELS IN 20 NEW HOUSES WITH MECHANICAL VENTILATION SYSTEMS

Gary Proskiw, P.Eng. **Peter Piersol, P.Eng.** **Mark Riley**

ABSTRACT

Formaldehyde levels were monitored over a one-year period in 20 new, low-leakage, occupied bungalows of similar size and layout. All contained some form of mechanical ventilation system ranging from bathroom exhaust fans to heat recovery ventilators. Sixteen were built to the R-2000 standard for energy-efficient housing, while four were relatively conventional structures. Formaldehyde levels were observed to be consistently lower in the R-2000 group of houses (which contained the more sophisticated ventilation systems) than in the conventional group of houses. The ASHRAE-recommended exposure guideline for formaldehyde of 0.10 ppm was found to be readily achievable, while the Canadian Federal-Provincial target level of 0.05 ppm could not be reached on a consistent basis using ventilation as the only formaldehyde control measure. Homeowner intervention with the mechanical ventilation systems was found to be a significant problem. It was concluded that mechanical ventilation rates must be established both on the ability of the system to remove pollutants as well as the effect the ventilation rate will have on homeowner intervention. To reduce intervention, ventilation systems must be perceived by homeowners as unobtrusive in terms of energy cost, noise, and comfort. For the houses studied, there was found to be little reduction in mean formaldehyde levels at or above total air change rates exceeding approximately 0.35 ach, which represented an average mechanical ventilation rate of approximately 0.30 ach.

INTRODUCTION

Formaldehyde (HCHO) is a colorless gas found in the indoor and outdoor environments. At elevated levels, such as those sometimes encountered indoors, the gas has a pungent odor. Although formed naturally outdoors, most formaldehyde found in residential environments originates from manufactured goods, materials, and substances used inside the house. Significant sources in new houses may include particleboard, medium-density fiberboard, and hardwood plywood paneling. Consumer products such as draperies, clothing, tapes, and some household chemicals use formaldehyde as constituents of glues or coatings. Cigarette smoke also contains formaldehyde.

Formaldehyde is a suspected carcinogen as well as a sensory irritant, primarily affecting the respiratory and nasal passages and the eyes. Like most indoor pollutants, individuals display varying tolerances although some people, particularly those with chemical sensitivities, are strongly affected by its presence.

For the builder, formaldehyde which originates from construction materials is particularly significant, since the builder can, in theory, exercise some control over the selection and use of those materials. Emission rates from construction materials may vary significantly with time and ambient conditions. They have been demonstrated to increase at elevated temperatures and with increased moisture content of indoor air (Godish and Rouch 1986). Emission rates will generally decrease with time as the chemical is depleted from the exposed surfaces of the material, although this process may extend over several years.

Emission rates from manufactured products may also be affected by the existing formaldehyde concentration in the ambient air, although the evidence is somewhat contradictory. Nelms et al. (1986) investigated emission rates of commercially produced particleboard using a test chamber with varying ventilation rates and material loadings and found that emission rates increased with lower ambient formaldehyde concentrations. However, Godish and Rouch (1987) investigated formaldehyde source interactions in a full-size house and in test chambers but were unable to reproduce chamber results in the full-size structure.

The Canadian formaldehyde exposure guidelines for residential air, as set by the Federal-Provincial Advisory Committee on Environmental and Occupational Health (1987), are 0.05 ppm as a target level and 0.10 ppm as an action level. ASHRAE Standard 62-1981 (ASHRAE 1981) recommends 0.10 ppm for long-term residential exposures.

RESEARCH PROGRAM

Project Houses

The project houses were located in Winnipeg, Canada, and had been constructed in 1985 and 1986 by a single builder. The structures were very similar in size and layout; two floor plans were used with main floor areas, based on interior dimensions, of 60 m^2 and 85 m^2 (646 ft^2 and 915 ft^2), respectively. All had full basements. Sixteen were designed to the R-2000 standard, with the remaining four constructed using relatively conventional practices. The R-2000 standard for residential construction includes requirements for building energy usage, airtightness, heating equipment, and mechanical ventilation systems.

The mechanical ventilation systems used in the houses ranged from intermittent, small-capacity bathroom exhaust fans to heat recovery ventilators (HRV) designed to run continuously and provide outdoor air distribution to all zones of the house. Sixteen of the mechanical systems utilized multi-speed controls which permitted flow rates to be automatically or manually adjusted.

Ten of the houses used high sidewall supply registers to minimize discomfort problems near the supply registers caused by continuous operation of the air distribution system. This technique introduces the heating/ventilation air in a horizontal plume close to the ceiling, permitting mixing and warming of the supply air before it reaches the occupied zone of the room. The 14 houses that used forced air heating systems also employed individual room return air registers to

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TABLE 1

Description of Project Houses

Houses	Year of Completion	Space Heating System	Ventilation System	Predominant Location of Heating/Ventilation Supply Registers	Energy Performance Standard
#1 to #6	1985	Forced Air Electric Furnace	Heat Recovery Ventilator Connected to Furnance Ductwork	Floor-Mounted	R-2000
#7, #8	1985	Forced Air Electric Furnace	Central Exhaust	Floor-Mounted	Conventional
#9, #10	1985	Forced Air Gas Furnance	Bathroom Exhaust Fan	Floor-Mounted	Conventional
#11, #12	1986	Electric Baseboards & Small Capacity Heat Pump	Exhaust-Only Heat Pump Heat Recovery Ventilator	High Sidewalls	R-2000
#13, #14	1986	Forced Air Electric Furnace	Heat Recovery Ventilator Connected to Furnace Ductwork	High Sidewalls	R-2000
#15, #16	1986	Integrated Forced Air Heating/Ventilation System	Air-to-Air Electric Heat Pump	High Sidewalls	R-2000
#17 to #20	1986	Electric Baseboards	Heat Recovery Ventilator with Dedicated Supply Ductwork	High Sidewalls	R-2000

provide better circulation when interior doors were closed. The effect of these two measures would likely have produced an above-average mean ventilation system efficiency for the houses.

Ventilation rates for the R-2000 houses were established to conform to the R-2000 Home Program Design and Installation Guidelines for Ventilation Systems (Energy, Mines and Resources Canada 1986), which require a minimum continuous mechanical ventilation rate of 0.35 ach (or greater, depending on the number of rooms).

All of the houses, including the conventional structures, were constructed with tight building envelopes to minimize air infiltration. Airtightness levels, determined in accordance with CGSB Standard 149.10-M (CGSB 1986), ranged from 0.44 to 2.20 ach at 50 Pascals when measured in February 1987. Potential sources of formaldehyde used in the construction of the houses included waferboard subfloors and particleboard cabinets.

No other measures, aside from the mechanical ventilation systems, were used to control formaldehyde levels. A more detailed description of the houses is given in Table 1.

MONITORING PROGRAM

Formaldehyde levels, total air change rates, and concentrations of other pollutants were monitored in March 1986, August 1986, October 1986, and February 1987 using passive diffusion dosimeters. Two dosimeters were installed for each test, with one located in the main bedroom and the second in the living/dining area. Exposure periods were approximately one week. Laboratory analysis was performed using a modified chromotropic acid method (Taylor 1981).

Total air change rates were measured simultaneously during three of the four sampling periods using the capillary adsorption tube sampling (CATS) technique (Dietz and Cote 1982). This method has been found to display good agreement with the constant concentration sulphur hexafluoride technique when relatively constant total air change rates are encountered (Piersol and Mayhew 1987). Four calibrated sources that emitted an inert perfluorocarbon tracer gas were situated around the house on exterior walls. Two or four samplers that adsorbed the tracer were installed at central locations on each level of the house. The amount of tracer adsorbed by the samplers was then related to the total air change rate experienced by the house during the monitoring period. Gas chromatographic analysis of the samplers was then performed.

Electrical timers were installed on the mechanical ventilation systems in 18 houses to determine their usage patterns. Additional information on house performance and occupancy was obtained through regular contact with the homeowners.

Average indoor dry-bulb temperatures were measured at a central location in the living/dining areas using thermohygrographs operating continuously during the monitoring periods. Mechanical ventilation system flow rates were measured using eight-point pitot tube flow-measuring stations permanently installed in the ductwork.

RESULTS

Observed formaldehyde and total air change rate data are summarized in Tables 2 and 3. Mean formaldehyde levels were calculated as the average of the two measurements performed in each structure during each test. Formaldehyde data are also presented based on the presence of smokers in the house.

During the routine site visits, several of the ventilation systems were found to have been operated at non-design conditions during the air quality monitoring. Data from these houses were isolated and are presented in Table 4, which gives a breakdown of formaldehyde results for those houses in which the ventilation systems were: a) operated in "nominal" compliance with the ventilation guidelines and b) actually operated in compliance with the guidelines, as verified by examination of the independently measured air change rate data. "Nominal" compliance was defined as instances in which the measured HRV flow rates were, at the time of the site visits, found to equal or exceed the minimum level specified by the R-2000 standard.

TABLE 2

Formaldehyde Levels

	Number of Houses	Mean (ppm)	Standard Deviation (ppm)	Median (ppm)	Measurements >0.05 ppm Number	%	Measurements >0.10 ppm Number	%
R-2000 Houses								
March 1986	6	0.061	0.016	0.060	4	67%	0	0%
August 1986	16	0.058	0.023	0.057	10	63%	1	6%
October 1986	16	0.080	0.028	0.072	16	100%	2	13%
February 1987	16	0.057	0.021	0.057	9	56%	1	6%
Cumulative	54	0.064	0.025	0.061	39	72%	4	7%
Conventional Houses								
March 1986	4	0.078	0.029	0.077	3	75%	1	25%
August 1986	4	0.067	0.014	0.065	4	100%	0	0%
October 1986	3	0.090	0.021	0.086	3	100%	1	33%
February 1987	4	0.067	0.019	0.060	4	100%	0	0%
Cumulative	15	0.074	0.021	0.066	14	93%	2	13%
R-2000 Houses								
Forced Air Heating Systems	36	0.063	0.027	0.058	25	69%	3	8%
Baseboard Heating Systems	18	0.067	0.020	0.064	14	78%	1	6%
R-2000 & Conventional								
Smokers	32	0.065	0.016	0.063	28	88%	2	6%
Non-Smokers	37	0.068	0.029	0.063	25	68%	4	11%

TABLE 3

Total Air Change Rates

	Number of Houses	Mean (ach)	Standard Deviation (ach)	Median (ach)	Measurements >0.40 ach Number	%	Measurements >0.50 ach Number	%
R-2000 Houses								
March 1986	6	0.28	0.18	0.26	5	83%	1	17%
October 1986	16	0.30	0.16	0.29	11	69%	2	13%
February 1987	15	0.43	0.13	0.45	4	27%	4	27%
Cumulative	37	0.35	0.16	0.36	20	54%	7	19%
Conventional Houses								
March 1986	4	0.16	0.05	0.14	4	100%	0	0%
October 1986	4	0.15	0.05	0.17	4	100%	0	0%
February 1987	4	0.20	0.07	0.18	4	100%	0	0%
Cumulative	12	0.17	0.05	0.17	12	100%	0	0%

DISCUSSION

Observed mean formaldehyde levels for the two groups of houses (R-2000 and conventional) were generally consistent during the March 1986, August 1986, and February 1987 monitoring periods, while elevated levels were encountered in October 1986. For each monitoring period, the mean formaldehyde level in the R-2000 group of houses was lower than the mean level for the group of conventional structures.

The majority of measured levels were between 0.05 ppm and 0.10 ppm, values representing the Canadian target level and the ASHRAE guideline, respectively. The mean formaldehyde level in the R-2000 houses was 0.064 ppm, with 72% of the measurements exceeding 0.05 ppm and 7% greater than 0.10 ppm. As noted above, this includes results from houses that were not operated in compliance with the R-2000 standard. In the conventional structures, the mean formaldehyde level was 0.074 ppm, with 93% and 13% exceeding 0.05 ppm and 0.10 ppm, respectively.

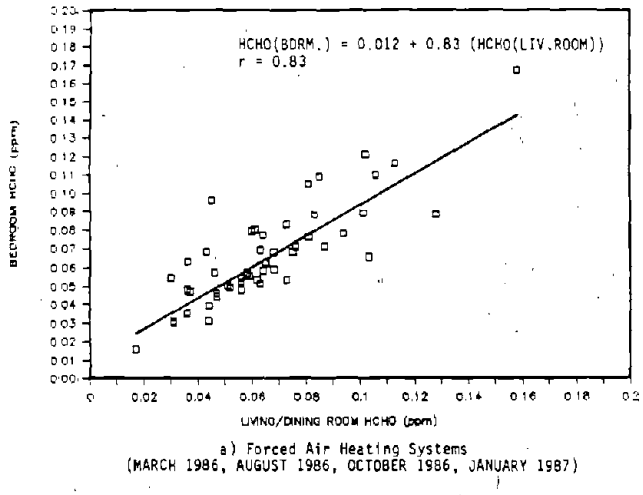
From a standards perspective, the goal of 0.10 ppm was

TABLE 4

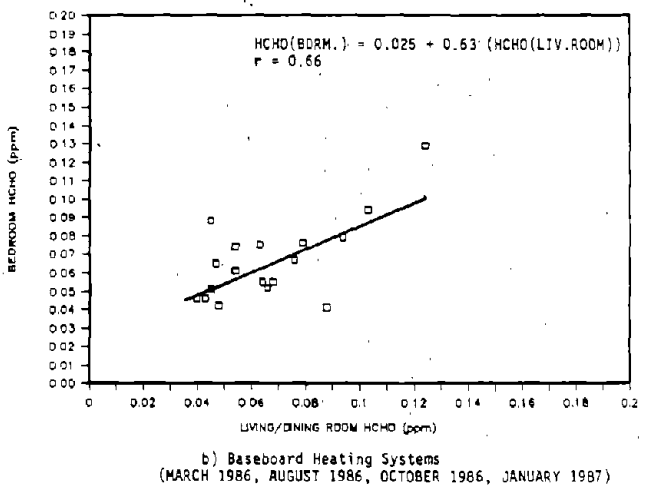
Effect of "Nominal" & Actual Compliance with R-2000 Ventilation guidelines Upon Formaldehyde Levels

1		2	
OCTOBER 1986	#1, #3, #4, #5, #13, #14, #20	OCTOBER 1986	#5, #14, #20
FEBRUARY 1987	#1, #2, #3, #4, #5, #13, #14, #19, #20	FEBRUARY 1987	#1, #2, #3, #5, #14, #19, #20
FORMALDEHYDE:			
n		16	10
Mean		0.070 ppm	0.055 ppm
Standard Deviation		0.031 ppm	0.014 ppm
Median		0.064 ppm	0.058 ppm

1. Houses operated in compliance with the R-2000 ventilation guidelines, as determined by a single measurement of the HRV flow rate.
2. House *actually* operated in compliance with the R-2000 ventilation guidelines.



a) Forced Air Heating Systems
(MARCH 1986, AUGUST 1986, OCTOBER 1986, JANUARY 1987)



b) Baseboard Heating Systems
(MARCH 1986, AUGUST 1986, OCTOBER 1986, JANUARY 1987)

Figure 1 Measured bedroom formaldehyde levels vs. living/dining room formaldehyde levels (March/86, August/86, October/86, January/87)

found to be readily achievable given the use of a quality mechanical ventilation system. However, to achieve 0.05 ppm on a consistent basis would have required additional measures such as source control.

Homeowner intervention with the ventilation system was found to be an important factor affecting formaldehyde levels. Houses operated in "nominal" compliance with the R-2000 standard had measured HRV flow rates sufficient to provide a minimum mechanical ventilation rate of 0.35 ach. However, in approximately one-third of these cases, the independently measured total air change rate was found to be substantially lower than the values indicated by the HRV flow measurements. Investigation revealed that homeowners had adjusted the HRV speed control or disconnected the power supply to the unit. Those houses independently verified to have been operated at the design ventilation rate demonstrated lower formaldehyde levels and reduced standard deviations. The mean value of 0.055 ppm and standard deviation of 0.014 ppm were similar to those reported by Piersol and Mijailovic (1987) for a broader population of R-2000 houses.

The issue of homeowner intervention is significant from the perspective of ventilation standards. The homeowners in the project houses received instructions on the purpose and use of the ventilation systems, including the need for continuous system operation. However, discussions with them indicated that many were reducing ventilation rates to cut energy costs, control noise, or reduce drafts. If any of these factors were perceived by the homeowners to be excessive, the flow rate was generally reduced. This raises the concern that ventilation systems with "high" design flow rates could inadvertently result in degraded air quality by increasing the frequency of homeowner intervention. (The "design" flow rate is defined here as the continuously operating ventilation rate.) Conversely, systems with lower design flow rates might experience less intervention and, subsequently, better air quality would be achieved.

Mean formaldehyde levels were found to be similar in houses that contained a smoker as compared to those that did not. This was a surprising observation since tobacco smoke is recognized as a formaldehyde source. The observed behavior may be due in part to the slightly higher total air change rates experienced by the houses containing smokers (0.32 ach vs. 0.29 ach).

Figure 1 plots measured bedroom formaldehyde levels vs. living/dining room levels for houses with forced air and

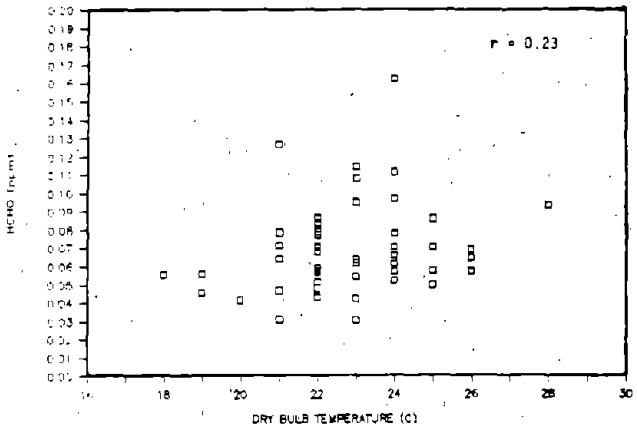


Figure 2 Formaldehyde vs. dry bulb temperature (March/86, October/86, January/87)

baseboard heating systems, respectively. Both R-2000 and conventional houses were included in the sample group. The degree of scatter about the regression line illustrates the effectiveness of the ventilation systems at achieving a well-mixed space in the houses. As evidenced by the plots and their respective correlation coefficients (0.83 and 0.66), the forced air systems provided superior mixing compared to the dedicated ventilation systems used in houses with baseboard heating.

Figure 2 plots mean formaldehyde levels vs. the average dry-bulb temperature recorded during the monitoring period. The correlation was observed to be weak over the range of temperatures encountered. The correlation coefficient, 0.23, suggests that temperature, by itself, was a weak indicator of formaldehyde concentration. Godish and Rouch (1986) were able to demonstrate a strong dependence between formaldehyde levels and temperature in an unoccupied mobile home, with other variables held constant, using indoor temperatures ranging from 20°C to 30°C.

Total air change rates in the R-2000 houses were generally low during the March 1986 and October 1986 periods because of homeowner intervention with the ventilation system or mechanical problems (typically motor burnouts or control malfunctions). During February 1987, after homeowners had been requested not to adjust the HRVs and any necessary repairs had been completed, mean levels increased to 0.43 ach. The average natural air infiltration rates for R-2000 houses is assumed to be 0.05 ach. Using this value, the estimated mean mechanical ventilation rate would have been 0.38 ach. This includes air change provided due to both continuous and peak operation of the ventilation system.

Mean formaldehyde levels are plotted against total air change rates in Figure 3. As shown, formaldehyde demonstrated a moderate dependence upon air change rates with a correlation coefficient of 0.65. Beyond approximately 0.35 ach, little reduction in measured formaldehyde levels was observed. Assuming a natural infiltration rate of 0.05 ach, the mechanical ventilation component of this figure would have been approximately 0.30 ach. Also, this value represents the combined air change rate due to operation of the system at all speeds so that the minimum required continuous rate would be less than 0.30 ach. However, it must be remembered that the project houses likely operated with above-average ventilation efficiencies as a result of the individual room returns used in 14 houses and the high sidewall supply registers in 10 of the structures. Also, they do not represent a random sample of house sizes and types. For comparison purposes, the design mechanical ventilation rate for houses using the 85 m² floor plan, calculated in conformance with the R-2000 standard, was determined to be 0.36 ach. The design mechanical ventilation rate capability calculated in conformance with the current draft of CSA F326.1, "Residential Mechanical Ventilation Requirements," (1988) was calculated to be 0.40 ach. This figure represents the design rate of the system, which does not necessarily have to be maintained at all times.

CONCLUSIONS

Detailed monitoring of 20 new, low-leakage, occupied houses equipped with mechanical ventilation systems found that a design goal for formaldehyde of 0.10 ppm was readily achievable, while a level of 0.05 ppm could not be reached on a consistent basis using mechanical ventilation as the only formaldehyde control measure. For each monitoring period, the mean formaldehyde level in the R-2000 group of houses was lower than the mean level for the group of conventional structures.

The results of the study indicate that the design mechanical ventilation rate must be established on the basis of both the ability of the system to remove pollutants as well as the effect the ventilation rate will have on homeowner intervention with the system. Homeowners tended to reduce the ventilation rate if they perceived the system as expensive to operate, noisy, or responsible for discomfort problems. Intervention appears to increase at higher design ventilation rates and may result in large reductions in the ventilation rate with a corresponding degradation of air quality.

For the houses studied, only nominal reductions were observed in mean formaldehyde levels at total air change rates, which exceeded approximately 0.35 ach. Assuming an average natural infiltration rate of 0.05 ach, the mechanical ventilation component of this figure would have been approximately 0.30 ach (comprising the net effect of both continuous and high-speed operation).

ACKNOWLEDGMENTS

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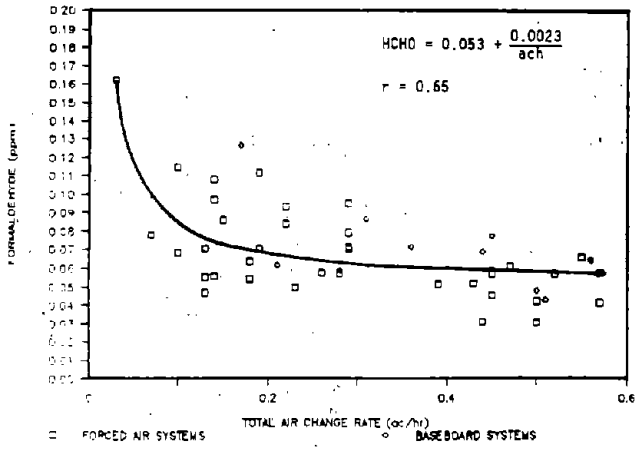

Figure 3 Formaldehyde vs. total air change rate (March/86, October/86, January/87)

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A PERSONAL MONITORING STUDY TO ASSESS WORKPLACE EXPOSURE TO ENVIRONMENTAL TOBACCO SMOKE

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ABSTRACT

Because the workplace may be the major or only site of exposure to environmental tobacco smoke (ETS) for some adults, we enrolled 15 nonsmoking volunteers to determine the feasibility of measuring personal exposure to ETS at work and to begin to characterize workplace exposures. We obtained exposure questionnaires, saliva, urine, and personal air particle samples during one workshift. Salivary and urinary cotinine was quantitated by a double antibody radioimmunoassay. Respirable particle and nicotine concentrations were determined from the personal air samples. The average duration of the workshift and of the personal monitoring was 6.5 hours (SD ± 2.0), with a mean reported hours of exposure of 3.4 (SD ± 2.1). Respirable particle and nicotine concentrations varied widely with the reported number of smokers and hours of exposure. As was observed for the atmospheric markers, the post-workshift urinary and salivary cotinine levels varied widely with self-reported exposure. We conclude that personal monitoring for tobacco smoke components could be accomplished in the workplace, and that personal RSP and nicotine, and urinary and salivary cotinine varied widely with self-reported exposure to ETS at work, but on average increased with increasing exposure.

INTRODUCTION

Passive smoking refers to the involuntary exposure of nonsmokers to the combination of tobacco combustion products released by the burning cigarette and smoke components exhaled by the active smoker (DHHS 1986; NRC 1986). Health effects of passive smoking on children and adults have been established, but the principal source of exposure investigated to date has been environmental tobacco smoke in the home. Exposure in the workplace has received little investigation and health effects of environmental tobacco smoke (ETS) in the workplace remain controversial.

Because the workplace may be the major or only site of exposure to ETS for some adults, we enrolled 15 nonsmoking adults to determine the feasibility of measuring personal exposure to ETS at work and to begin to characterize workplace exposures. Markers of exposure included questionnaires, personal respirable particles (RSP), and nicotine, and urinary and salivary cotinine were measured during a workday for each subject.

METHODS

Sample Selection

Between October 1986 and May 1987, 15 nonsmoking volunteers, 18 years of age and older, were recruited from the Albuquerque area to participate in a study of exposure to ETS at work.

Data Collection

We obtained exposure questionnaires, saliva, urine, and personal air particle samples during one workshift. From the questionnaires, we determined the reported number of smokers and number of hours that the subjects were exposed during their workshift. The saliva and urine specimens were obtained before and after the workshift.

Cotinine Assay

Cotinine was quantitated by a double antibody radioimmunoassay, as described by Langone et al. (1973). A specific antiserum produced in rabbits was supplied by Dr. Helen Van Vunakis. The saliva and urine samples were diluted 1:5 and 1:4 for the assay, respectively. The sensitivity of the assays in our hands was 0.20 ng/ml of saliva, and 0.78 ng/ml of urine. Urine creatinine concentrations were determined by the Jaffe reaction (Faulkner and King 1976), and the urine cotinine concentrations were standardized to the creatinine concentrations. Assays were performed without knowledge of questionnaire responses.

Particle Measurements

During the workshift, each subject wore a personal monitoring pump with a 10 mm nylon cyclone clipped to the shirt collar (Turner et al. 1979). RSP samples (2.5 μm cutpoint) were collected on 37 mm filters and nicotine was collected on a glass fiber backup filter treated with sodium bisulfate to minimize volatilization. After extraction from the filter, analysis for nicotine was done on a gas chromatograph with a flame ionization detector. The nicotine collection and extraction procedure is a modification of that described by Hammond et al. (1987). The recovery of nicotine by this procedure has been shown to be 98% efficient.

Data Analysis

The questionnaire responses, respirable particle and nicotine concentrations, and urinary and salivary cotinine levels were assessed with univariate analyses. From the questionnaires the measures of exposure included the total number of cigarette smokers and total number of hours exposed during the workshift.

To describe the relationships among the measures of ETS exposure, Spearman correlations were calculated. Data analysis was performed with standard programs (SAS Institute 1985).

RESULTS

Of the 15 volunteers, there were eight males and seven females working in a variety of occupations. The mean age of all participants was 44.8 years (Table 1). The average du-

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TABLE 1

Description of Participants in a Personal Monitoring Study of Exposure to Environmental Tobacco Smoke at Work, New Mexico, 1986–7

Sex	Age (years)	Occupation/Workplace	Workshift Duration (hours)
Males			
1	30	Physician/Hospital	6
2	34	Social Worker/Office	8
3	33	Stock Broker/Office	8
4	41	Bus Boy/Restaurant	8
5	49	Maintenance Worker/Retail Store	8
6	52	Barber/Barber Shop	8
7	52	Barber/Barber Shop	8
8	70	Volunteer/Hospital	4
Females			
9	25	Interviewer/Public Transportation	3
10	31	Travel Agent/Office	8
11	36	Travel Agent/Office	6
12	34	Attorney/Office	8
13	63	Volunteer/Hospital	4
14	60	Volunteer/Hospital	4
15	62	Volunteer/Hospital	4

TABLE 2

Spearman Correlations Between Various Measures of Environmental Tobacco Smoke at Work, New Mexico, 1986–7

Correlated Measures	N	r
RSP ($\mu g/m^3$) with:		
Nicotine	15	0.57*
Total number of smokers	15	0.44
Total hours of exposure	15	0.53*
Postshift urine cotinine	14	0.05
Postshift saliva cotinine	11	−0.07
Nicotine ($\mu g/m^3$) with:		
Total number of smokers	15	0.62*
Total hours of exposure	15	0.54*
Postshift urine cotinine	14	0.60*
Postshift saliva cotinine	11	0.46
Postshift urine cotinine (ng/mg Cr) with:		
Total number of smokers	14	0.39
Total hours of exposure	14	0.57*
Postshift saliva cotinine (ng/ml) with:		
Total number of smokers	11	0.63*
Total hours of exposure	11	0.45

*$p < 0.05$

ration of the workshift and of the personal monitoring was 6.5 hours (SD ± 2.0).

Exposure to cigarette smokers at work was reported by 13 of the 15 participants. Of the 13 reporting exposure, two reported exposure to crowds of smokers during their workshift and the remaining 11 encountered a mean of 8.8 smokers (SD ± 6.7). The mean reported hours of exposure was 3.4 (SD ± 2.1).

Respirable particle and nicotine concentrations varied widely with the reported number of smokers and hours of exposure (Figures 1 through 4). The mean concentrations for RSP and nicotine were 63.9 $\mu g/m^3$ (SD ± 41.5) and 20.4 $\mu g/m^3$ (SD ± 20.6), respectively. Correlations between the atmospheric markers and the questionnaire measures of exposure to ETS were moderate (Table 2).

As was observed for the atmospheric markers, the postworkshift urinary and salivary cotinine levels varied widely with self-reported exposure. In comparison with pre-workshift levels, post-workshift levels were not consistently increased. The mean pre-workshift urinary and salivary cotinine concentrations were 31.8 ng/mg Cr (SD ± 67.6) and 2.9 ng/ml (SD ± 5.0), respectively. For the post-workshift levels, the corresponding values were 19.7 ng/mg Cr (SD ± 43.2) and 3.5 ng/ml (SD ± 5.9).

To examine the relationships among the questionnaire variables, the atmospheric markers, and urinary and salivary cotinine, the authors calculated Spearman correlations (Table 2). Moderate correlations were obtained for self-reports and cotinine levels, and nicotine levels and cotinine levels. However, there was no correlation between RSP levels and cotinine concentrations.

DISCUSSION/CONCLUSIONS

In a group of 15 nonsmoking volunteers, it was found that personal RSP and nicotine, and urinary and salivary cotinine varied widely with self-reported exposure to ETS at work but on average increased with increasing exposure. Personal monitoring for tobacco smoke components could be accomplished in the workplace. However, many people approached for participation refused because of concern about potential responses from the employer or coworkers.

We observed moderate correlations among the questionnaire measures, the results of personal monitoring for RSP and nicotine, and measurements of urinary cotinine. Each of these types of measures provides a differing index of exposure to ETS. The questionnaire measures that were used assess source strength, but concentrations of ETS are also influenced by room volume and ventilation. Nicotine is a specific marker of exposure to ETS, whereas RSP is nonspecific. Cotinine levels reflect nicotine exposure, but are also determined by individual differences in uptake and metabolism. Thus, tight concordance among the broad indicators of exposure used in this study would not be anticipated. The authors consider these approaches to be complementary for measurement of exposure to ETS.

As anticipated, the nicotine measurements were correlated with the cotinine values, whereas the RSP measurements were not. We conclude that personal sampling for nicotine represents a specific approach for assessing ETS exposure in the workplace. However, because of the small sample size and the limited assessment of self-reported exposure, additional research is warranted to further characterize the relationships among these various markers of exposure to ETS in the workplace.

ACKNOWLEDGMENTS

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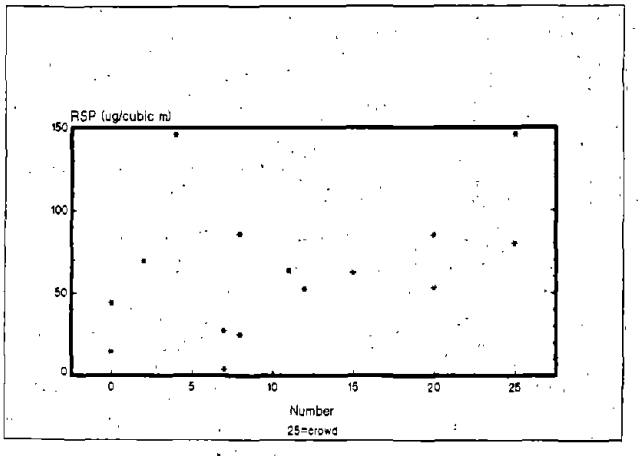

Figure 1 *Personal RSP concentrations vs. the self-reported number of cigarette smokers exposed to at work*

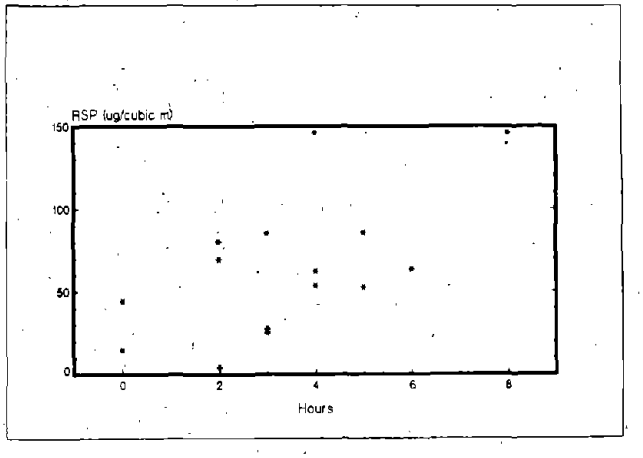

Figure 2 *Personal RSP concentrations vs. the self-reported hours of exposure to cigarette smokers at work*

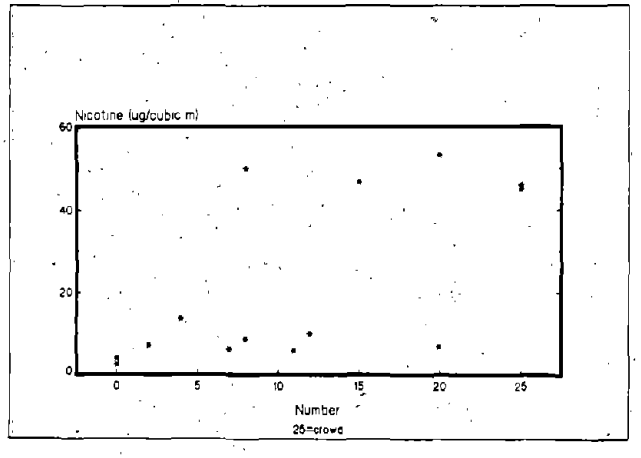

Figure 3 *Personal nicotine concentrations vs. the self-reported number of cigarette smokers exposed to at work*

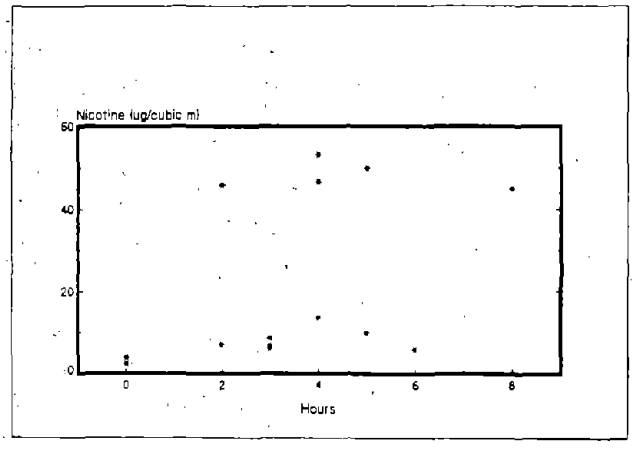

Figure 4 *Personal nicotine concentrations vs. the self-reported hours of exposure to cigarette smokers at work*

RESOLUTION OF THE SICK BUILDING SYNDROME: PART II. MAINTENANCE

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ABSTRACT

Many cases of suspected sick building syndrome (SBS) have been investigated and, in virtually all cases, a physical basis has been hypothesized for resolution of SBS symptoms. However, psychosocial factors also existed in many of these cases. The physical causes seem to occur in four primary categories: lack of proper maintenance, changes in loads from original design, changes in control strategies to meet new objectives (e.g., energy conservation), and inadequate design.

In this paper, we concentrate on findings regarding four categories of maintenance deficiencies: (1) building structure; (2) heating, ventilating, and air conditioning (HVAC); (3) general housekeeping; and (4) a comprehensive maintenance program. Six buildings, which exhibited deficiencies in one or more of these categories, serve as cases for this discussion. Recommended solutions are presented.

Based on our observations of these and other cases, we conclude that with proper attention to maintenance aspects and a comprehensive understanding of HVAC system performance, resolution of SBS is achievable in most buildings.

INTRODUCTION

Energy conservation measures that have been initiated since the 1973 oil embargo have, in many instances, greatly reduced the ventilation of buildings. During this same period, there has been a proliferation of the use of synthetic materials and office automation equipment (e.g., copiers and printers). The increased use of manufactured wood products, carpeting, adhesives that contain volatile organic compounds (VOC), and the increased use of photocopy machines that often emit VOC, ozone, and particulates have all added to the need for increased ventilation. As a result of these emissions and low ventilation rates, some building occupants began to notice irritation soon after entering a particular building and almost immediate relief upon leaving the building.

Occurrences such as these led to the coining of the phrase "sick building syndrome" (Stolwijk 1984) to describe the effects of indoor air contaminants on the building occupants. International indoor air quality experts have essentially agreed that a building manifests SBS when: 1) complaints of certain symptoms associated with acute discomfort (e.g., headaches, fatigue, eye irritation, sore throat, nausea) persist at frequencies significantly greater than 20%; 2) the cause or causes of the complaints are not recognizable; and 3) a substantial percentage of the complainants report almost immediate relief upon exiting the building. Strong evidence of building-related problems is immediate relief from the symptoms upon leaving the building.

INVESTIGATIVE PROCEDURES

The protocol used for evaluating indoor air quality in non-industrial buildings is based on the principles of building diagnostics (Building Research Board 1985). The diagnostic procedure is based on a three-phase approach (Woods et al. 1987): consultation, qualitative diagnostics, and quantitative diagnostics. All of the cases reported in this paper, except one, were diagnosed under Phase 1 of our three-phase approach. Phase 1 does not involve any physical data recording (i.e., it consists mainly of information-gathering meetings, discussions with occupants, and a walkthrough) and hence a limited amount of information is available. Although some occupants in the cases presented here manifested SBS symptoms, the objectives of the investigations were not to explicitly demonstrate the existence of the syndrome. Rather, the objectives were to identify recommendations that would mitigate the symptoms and complaints.

Many cases of suspected SBS have been investigated, and physical causes for occupant complaints have been documented. Psychosocial factors also existed in many of the cases investigated. Often the psychosocial factors involved employee distrust of management that resulted from a perceived no-action response by the management to employee complaints. Job satisfaction was also suspected as part of the psychosocial issues in some of the cases. This paper addresses only the suspected physical causes and not the aggrandizing psychosocial factors.

We have found that the physical causes for SBS fall into four major areas:

1. Lack of system maintenance,
2. Changes in control strategies to meet new objectives during the lifetime of the building (e.g., energy management, cost containment),
3. Changes to thermal and contaminant loads imposed during the lifetime of the building, and
4. Inadequate design of the original system or building.

In a previous paper presented at IAQ '87 (Woods et al. 1987), we concentrated on findings regarding design deficiencies. In this paper, we will focus on inadequate maintenance. Many other investigators (Binnie 1988; Chow and Wang 1987; Collett et al. 1988; Ferahian and Mice 1988; Gibbs 1987; Morey 1988; Robertson 1988) have reported on maintenance deficiencies found in buildings with SBS or building-related illness-type symptoms. We have found four categories of maintenance deficiencies:

1. Building structure,
2. HVAC,
3. General housekeeping, and
4. Comprehensive maintenance program.

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Examples of these maintenance deficiencies and their proposed solutions are presented here.

FIELD EXAMPLES

The maintenance deficiencies in six different buildings are described to illustrate the various classes of problems. Often, the same building exhibited deficiencies in one or more of the four categories. SBS complaints have been exhibited in each of the example buildings.

Building 1

Building 1 was a 25-year-old, five-story municipal building of approximately 300,000 ft². The building was air-conditioned by four separate HVAC systems. The HVAC systems were located in a penthouse on the roof of the building, and each system served a quadrant (all floors) of the building. The systems were constant-air-volume (CAV), dual-duct systems. On each of the systems, there were "throwaway" fiberglass pre-filters on the outdoor air intakes, inoperative (no longer used) electronic air cleaners (EAC) in the mixed air, and "throwaway" pleated paper filters in the mixed air. Individual mixing boxes were used to condition the perimeter offices and the building core was served by four mixing boxes per floor.

Occupants of diagnosed areas cited temperature conditions as a problem and some occupants complained that the space was "stuffy." Occupants of the basement and first floor reported—in addition to temperature complaints—headaches, fatigue, and drowsiness. These symptoms reportedly went away upon leaving the building. Based on our Phase 1 investigation, Building 1 suffered from maintenance deficiencies in the following categories: HVAC, general housekeeping, and comprehensive maintenance program.

There were missing pre-filters in each of the four HVAC systems. The old EACs had not been operated in years and the collector plates were caked with layers of dirt. The interior walls of the mixed air plenum, both upstream and downstream of the EAC, were also covered with dirt. There were two floor drains in the mixed air plenum for the EAC automatic wash cycle. The traps of both drains were dry, thereby allowing sewer gases to enter the mixed air plenum. The ductwork was rusted through under the cooling coils on two of the units. The condensate water would run out of the duct in three or four different places and into a maze of troughs that would catch the water and channel it off to a nearby floor drain. The perimeter mixing box units were very dirty and some of the units did not function properly. Another sign of poor maintenance of the mixing box units was old, moldy food lying in them.

Housekeeping was inadequate in many areas of the building. What appeared to be years of accumulation of dust and dirt was on some of the windowsills. Due to a shortage of storage space, employees were placing articles on top of the perimeter units, thereby blocking a portion of or most of the units' discharge. Overcrowding in some offices resulted in file cabinets being placed in front of low sidewall return air grilles, thereby severely restricting the return airflow.

There was a complete absence of a comprehensive maintenance policy. Filters were changed on a regular basis but that was all. Other maintenance was done only on an as-needed basis. The "chief engineer" and his "righthand man" were relatively new to the job, did not understand the HVAC system, and had not had any type of training on the systems. The lack of training was probably partly responsible for the absence of a comprehensive maintenance program.

As a result of the Phase 1 investigation, the following recommendations were made to mitigate the problems:

- Clean the plenums of the air-handling units, replace missing pre-filters, and keep the traps for the floor drains full of water or seal them off. It was further recommended that an engineering study be conducted to determine if the HVAC systems should be renovated or replaced. At a minimum, the rusted-through ductwork should be replaced and the cooling coil drain pans repaired. The perimeter mixing box units should be checked and repaired if necessary to ensure that all are in proper working order.
- The housekeeping procedures should be reviewed and changed where necessary. Where necessary, offices should be rearranged so file cabinets will no longer block return air grilles. The employees should be informed that material should not be placed on top of the supply outlets of the perimeter mixing box units.
- A comprehensive maintenance program for the building should be developed. Part of the program should include training for the building engineer and engineering staff.

Building 2

Building 2 was a 22-story, multi-tenant office tower. The building was 32 years old and had approximately 20,000 ft² per floor. There were separate HVAC systems on each floor (for air-conditioning the core on that particular floor) and four HVAC systems (two in the basement and two on the roof) that supplied perimeter induction units on all floors of the building. All of the HVAC systems were CAV units. Prefilters in the outdoor air were of the fiberglass throwaway type and the filters in the mixed air were pleated paper. The HVAC equipment was the original equipment but it had been meticulously maintained.

Occupants reported regularly experiencing symptoms of headache, nasal and sinus congestion, coughing, eye irritation, and difficulty wearing contact lenses. The complainants indicated that their symptoms diminished shortly after leaving work.

Based on our Phase 1 investigation, Building 2 had maintenance problems in the following categories: building structure and HVAC.

The structural design problem involved two of the outdoor air intakes. The building was located on a corner with busy streets in front of and on one side of the structure. There were alleys on the other two sides of the building. The outdoor air intakes for the two HVAC systems in the basement were located at street (alley) level on the back side of the building. The problem was caused by transients who slept in the alley and used the outdoor air intakes as urinals. The garbage dumpsters for the building were also kept at one end of the alley, and garbage odors were entering the outdoor air intake closest to the dumpsters.

The other problem resulted from a maintenance deficiency of the HVAC system, even though a comprehensive maintenance program existed. The central mechanical equipment was meticulously maintained but the perimeter induction units were only serviced on an as-needed basis and cleaned only infrequently. The reason for this was that office remodeling had made the units very difficult to access and hence they were neglected.

As a result of the Phase 1 investigation, the recommended solutions to mitigate these problems were:

- Erect gates at both ends of the alley to keep out transients and raise the outdoor air intake by the dumpsters to minimize the entrainment of garbage odors.

- All of the perimeter induction units should be cleaned and put back on a regular maintenance schedule.

Building 3

Building 3 was a two-story office building, seven years old, with 176,000 ft² of total floor area. The building was conditioned by four HVAC systems: one multi-zone unit, two CAV units, and one VAV unit. "Throwaway" fiberglass filters were used on the multi-zone system and pre-filters in conjunction with bag filters were used on the other three systems.

Both SBS symptoms and a suspected building-related illness (BRI) case were present. The reported symptoms typical of SBS included eye irritation, headache, rhinitis, and lethargy. All of the occupants who reported such symptoms also reported that their symptoms diminished upon leaving the building. The suspected BRI case involved one individual who was having respiratory allergic reactions.

Based on our Phase 1 investigation, Building 3 suffered from deficiencies in HVAC maintenance.

Maintenance of the HVAC systems was performed by an outside contractor and there was a comprehensive maintenance program in place. Filter and mechanical equipment maintenance were performed on a regularly scheduled basis. The problem was the sound liner in the discharge air plenum of the VAV system, which was heavily contaminated with *Penicillium*. A limited number of bulk samples were taken during this Phase 1 investigation for the purpose of identifying the fungal growth on the sound liner. It is suspected that the fungal growth was overlooked during routine inspections because the maintenance personnel were not trained to look for evidence of fungal growth nor were they familiar with the potential risk.

The recommended solution, resulting from our Phase 1 investigation, was to remove the sound liner from the plenum and disinfect the plenum with a dilute bleach solution. The plenum in this instance was large and hence it was more economical to remove the liner than to replace the plenum. Whether it is more economical to remove the liner or replace the ductwork generally will depend on its size and location. It is recognized that removing the sound liner will increase the noise transmission and installation of alternative noise-reducing methods (e.g., in-duct attenuators) may be required.

Building 4

Building 4 was a two-story office building with 100,000 ft² on the first floor and 25,000 ft² on the second floor. The building was originally constructed in 1960 as a warehouse with office space in the two-story portion of the building. It was completely converted to office space approximately six years ago. The two-story portion of the building was conditioned by two multi-zone HVAC systems. The mechanical equipment rooms housing each of the systems also acted as the mixed air plenum for the respective unit. "Throwaway" fiberglass filters were used on each of the two systems. The remaining single-story structure was air-conditioned by four VAV HVAC systems. All of the VAV systems had "throwaway" fiberglass filters.

Occupants reported symptoms of headaches, lethargy, and difficulty in concentrating. These symptoms reportedly diminished upon leaving the building. Temperature complaints and complaints of "stuffy" or "stale" air were also very common.

The problems in Building 4, based on our Phase 1 investigation, were in the following categories: building structure or envelope, HVAC, and no comprehensive maintenance program.

The building envelope problem was water leakage at the tops of the windows on one side of the building. The problem only occurred when it rained and the wind was from a direction that would drive the rain into the windows. The resulting leaks would wet the ceiling tiles along the windows. There was no evidence of microbial growth on the ceiling tiles but the potential for microbial-related problems definitely existed.

The HVAC problem was with the multi-zone units. The mechanical equipment rooms, which also functioned as mixed air plenums, were not clean and were used for storage of old pipe, old filter boxes, janitorial supplies, and miscellaneous items. Using the mixed air plenum for storage makes it harder to keep the plenum clean, it can add contaminants (e.g., dirt and VOC) to the supply airstream, and the cardboard boxes are nutrients for microorganisms that could, in turn, contaminate the supply air. An additional problem with the multi-zone systems was that a panel was missing on the left- and right-hand sides of the filter rack and this allowed some of the air to directly bypass the filters.

The chief engineer for the building and its HVAC systems had only obtained responsibility for the building days before our site visit. What the chief engineer inherited from the previous responsible party was no maintenance program of any kind, no maintenance records, and an incomplete set of engineering drawings. Maintenance people who had been associated with the building for a number of years indicated that the only regular maintenance was filter changing. Everything else was done on an as-needed repair basis.

As a result of our Phase 1 investigation, the following recommendations were made to mitigate the SBS problems experienced in Building 4:

- The windows leaking from wind-driven rain should be recaulked. All ceiling tiles that have been water damaged should be replaced.
- The missing filter rack panels on the two multi-zone units should be replaced. The mechanical equipment rooms housing the multi-zone units should be cleaned and all stored material removed.
- A comprehensive maintenance program for the building should be developed. A complete set of engineering drawings should be made available. A training program for the building engineer and his staff should be implemented, even if the maintenance program recommends using an outside contractor.

Building 5

Building 5 was a 12-story hospital with approximately 15,000 ft² per floor. The building was approximately 25 years old. The HVAC systems were located in the basement and in a penthouse on the twelfth-floor roof. All of the HVAC systems were CAV and some used recirculated air and others used 100% outdoor air. "Throwaway" fiberglass filters were used on some systems and pre-filters in conjunction with bag filters were used on other systems. The operating room HVAC systems were new, had HEPA filters, and were not included in the investigation. All three phases of our investigative approach were used in diagnosing this building.

Symptoms reported by occupants varied somewhat from one area to another, but symptoms common to all were headache, eye irritation, dry mucous membranes, drowsiness, and dry skin. Some occupants also reported unexplained memory loss. These symptoms reportedly diminished shortly

after leaving the building. Based on Phase 1, 2, and 3 investigations, the building suffered in all four problem areas: structure, HVAC, housekeeping, and comprehensive maintenance program.

There were two envelope- or structure-related problems. One was water leakage around the windows due to wind-driven rain and the other was building-related wind recirculation patterns which, at times, resulted in the kitchen exhaust contaminating the outdoor air intake. The caulking and grout around the windows was falling out and wherever it was missing, wind-driven rain would result in a water leak. The other structure-related problem involved the tower structure of the hospital and the location of the kitchen exhaust and outdoor air intake on the fifth-floor roof. Wind recirculation patterns sometimes would carry the kitchen exhaust up off the roof and then back down and directly into the outdoor air intake.

Most of the HVAC systems were original equipment and hence were approaching or at the end of their expected service life. Plenums and ductwork around cooling coils were rusted out due to condensate leaks or drain pan overflows. Some of the control functions had been disconnected or modified without regard, apparently, for the overall effect on system performance. The plenums in all of the systems were dirty and filter maintenance appeared to be erratic. The fan coil units around the perimeter appeared as though they were rarely, if ever, cleaned.

Housekeeping in areas other than patient care areas was very poor. Housekeeping practices such as using the corridors for storage and the handling of clean and dirty linen were inadequate. A portion of the problem was due to inadequate facilities and insufficient staff.

There was no comprehensive maintenance program in effect at the hospital. There was a filter replacement schedule but it was not followed very rigorously. Some of the systems were completely neglected and only attended to on an emergency basis.

As a result of our Phase 1, 2, and 3 investigations, the following recommendations were made to mitigate the problems:

- Repair and/or replace the caulking and grout around the windows to stop the wind-blown rain leakage problems.
- Initiate an engineering study to determine if the HVAC equipment should be replaced or renovated. Short-term recommendations were to clean the HVAC system plenums, clean the coils and drain pans, follow the filter replacement schedule, and clean the perimeter fan coil units.
- The budget for housekeeping should be increased to allow the hiring of an adequate staff. All housekeeping policies should be reviewed and updated where necessary. The housekeeping policies should be enforced to ensure that the work gets done.
- A comprehensive maintenance program should be developed and the budget increased to allow the implementation of the program. Included in the program should be HVAC training for the building engineer and his staff.

Building 6

Building 6 was constructed in 1971 and was six stories, two of which were below grade. The total area of the facility was approximately 92,000 ft^2. Basement level 1 housed a parking garage and two mechanical equipment rooms, which housed the HVAC equipment for the garage and basement level 2. A penthouse housed two additional mechanical equipment rooms that housed the HVAC equipment that air-conditioned floors 1 through 4. All of the HVAC systems were CAV.

Occupants reported experiencing symptoms of nausea, dizziness, eye and throat irritation, numbness in fingertips, and loss of depth perception. The occupants reported that their symptoms seemed to subside shortly after leaving the building.

Based on our Phase 1 investigation, the building suffered from maintenance problems in the following categories: building envelope, HVAC, and comprehensive maintenance program.

The envelope-related problem was the roof. A new insulated roof had been completed approximately one year prior to our site visit. The new roof was fabricated by spraying urethane foam over the old roof and then covering that with an elastomer spray coating. When the elastomer spray coating was applied, some of the roof drains were inadvertently plugged with the elastomer coating. As a result, there was inadequate drainage and a roof leak developed. The roof leak had caused some ceiling tiles to get wet, although at the time of our site visit there was no evidence of microbial contamination.

The maintenance deficiencies with the HVAC equipment were infrequent filter changing, dirty coils, and dirty drain pans. At the time of the site visit, the filters, coils, and drain pans in all of the air handlers were found to be dirty. Discussions with the building maintenance person indicated that the filters were changed on an "occasional" basis.

It was discovered that there was no comprehensive maintenance program in effect and efforts were just beginning to implement one. A few days before our site visit, the building manager had contracted with a maintenance firm to perform monthly HVAC equipment inspections and "as-needed" service.

The following recommendations, as a result of our Phase 1 investigation, were made to help mitigate the SBS problems in the building:

- Unplug the roof drains and ensure that there is adequate drainage of the roof. Repair the roof leaks and replace the damaged ceiling tiles.
- Replace air filters in all of the air handlers and clean the coils and drain pans.
- Develop a comprehensive maintenance program that includes all of the mechanical equipment, controls, and building structure. Such a program will help ensure that occupant health, well-being, and comfort are not being compromised while the systems are being operated cost effectively.

DISCUSSION

Through October 1988, we have investigated more than 50 cases, and it is estimated that approximately 75% of all cases have had maintenance deficiencies sited as one of the causes of their SBS complaints. A ranking—with most frequent being first—of the four maintenance deficiencies discussed in this paper would be: HVAC, comprehensive maintenance program, housekeeping, and building structure. Part of the maintenance problem, in many instances, is due to budgetary constraints and inadequately trained personnel. Building owners and/or managers may cut maintenance budgets without noticing any adverse effects for a period of time, maybe years. When problems do occur, such as SBS complaints, the managers may think that the people are complaining just for the sake of complaining. When the

complaints continue, the building manager or responsible party will often hire a consulting firm to come in and "check" the air. We suspect that inadequate maintenance is rarely thought to be part of the problem. Inadequately trained building engineering or maintenance personnel may also be indicative of the slashed budget problem. Often, building engineers and their associates are not adequately trained to operate and maintain an HVAC system.

CONCLUSION

Based on our observations, it is our opinion that when care is taken to ensure that the HVAC equipment is properly maintained, operated, and that an appropriate amount of outdoor air enters the building and is properly distributed, complaints can be minimized and resolution of the SBS is achievable in most buildings. Follow-up diagnostics are not typically requested by clients and hence final results are generally never known (i.e., what happened after recommendations were implemented). Speculation on the nature of the possible agent causing the complaints in each of the case buildings was not done because one of the characteristics of SBS is that the cause(s) of the complaints are not identifiable.

The existence of a comprehensive maintenance program is of the highest importance because such a program should include specifications for maintenance of the building structure and envelope (i.e., exterior walls, roof, etc.), maintenance of the HVAC equipment, and general housekeeping procedures. Key maintenance items to be included are:

—repair of all building envelope leaks,
—regularly scheduled filter changing in all HVAC equipment,
—regularly scheduled inspection, and replacement if necessary, of the air duct liner,
—regularly scheduled coil and drain pan cleaning,
—regularly scheduled maintenance of the mechanical equipment,
—regularly scheduled maintenance and calibration of the controls, and
—specification of the cleaning agents to be used in the occupied space as well as the cleaning schedule.

Furthermore, proper maintenance procedures will probably enhance the energy efficiency of the HVAC equipment while providing acceptable environmental conditions in the occupied spaces.

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DISCUSSION

Richard J. Shaughnessy, Center for Environmental Research and Technology, University of Tulsa, Tulsa, OK: For your diagnostics procedure, if required, what specific contaminants do you look for? I understand that Honeywell has specific criteria pollutants that will be examined and was interested in how these were chosen above others.

C.A. Lane, Honeywell Indoor Air Quality Diagnostics, Golden Valley, MN: Honeywell IAQD performs a three-phase diagnostics procedure to identify and solve indoor air quality problems in buildings. In the first phase (i.e., the consultation phase), the building is characterized as a "system" of components, which include the building structure, envelope, interior spaces, and the services (e.g., the HVAC systems). The purpose of this phase is to identify the relationship between the symptoms expressed by the occupants, the possible sources of contaminants, and the physical characteristics of the building systems. No objective data are obtained in this phase.

If additional diagnostics are required, the second phase (i.e., the qualitative diagnostics phase) is performed. Typically, this phase consists of an engineering analysis of the building systems, which includes a thermal and air contaminant loads analysis and an analysis of the HVAC control systems. Normally no data are obtained in this phase, except for occasional measurements (e.g., airflows, etc.) to characterize the performance of the HVAC systems servicing the complaint areas.

If additional diagnostics are required, the third phase (i.e., the quantitative diagnostics phase) is performed. In this phase, the areas of maximized exposure to contaminants, and the areas of the most susceptible occupants are identified. Objective data are obtained in these areas as well as performance data for the HVAC systems that service the areas. The specific data obtained will depend on the nature of the problem; however, sampling for carbon dioxide, total particulates, total hydrocarbons (i.e., FID detector), VOCs (i.e., Tenax sampling), illuminance, luminance, acoustics, dew point, dry-bulb temperature, mean radiant temperature, and air velocity is typically performed. Microbial sampling also will be performed if conditions indicate.

Honeywell IAQD uses performance criteria specified in ASHRAE Standards 55-1981 (i.e., thermal) and 62-1981R (i.e., indoor air quality), and IES standards. IAQD has elected to establish performance criteria for gaseous contaminants that are based on the lower concentration of either one-tenth the TLV or twice the odor threshold value.

A STUDY OF DIESEL FUME ENTRAINMENT IN AN OFFICE BUILDING

F.J. Offermann *ASHRAE Member* **S.A. Loiselle** **M.C. Quinlan** **M.S. Rogers**

ABSTRACT

The authors used a tracer gas technique to study diesel fume entrainment into a high-rise office building where the tenants of the building have had a history of health-related complaints. The primary symptoms reported by the building tenants included headache and nausea. In addition, tenants reported noticing a strong diesel odor at various times and days of the week. The building is situated in the downtown area of a large city and directly over an underground train station. Diesel emissions from the underground trains parked at the station are vented to street level through a series of steel grates in the sidewalk. The outdoor air inlet associated with the building ventilation system serving the area with the health complaints is situated on the building wall 10 ft above the sidewalk and is directly above one of these exhaust grates. We simultaneously measured the indoor and outdoor concentrations of carbon monoxide and nitrogen oxides during the afternoon commute period. The indoor concentrations of carbon monoxide ranged from 5 to 14 ppm. The outdoor concentration of carbon monoxide in the vicinity of the outside air inlet peaked at 50 ppm during train movement.

The indoor concentrations of nitrogen dioxide ranged from < 0.05 ppm to 0.25 ppm. The outdoor concentration of nitrogen dioxide in the vicinity of the outside air inlet was observed to average 0.65 ppm over a two-hour measurement period. We used a tracer gas technique to determine the percent of sidewalk exhaust emissions entering the building. We injected sulfur hexafluoride gas at a constant flow rate into three of the exhaust grates and collected both instantaneous syringe samples and time-integrated bag samples at indoor locations, the outside air duct, and at an outdoor location in the vicinity of the outside air inlet. We used a gas chromatograph with an electron capture detector to measure the tracer gas concentrations over a range of 0.1 ppb to 50 ppb. We computed the total entrainment of the sidewalk exhaust to be 5.8% and 4.5% for a consecutive pair of tests. We also calculated the entrainment through the outside air inlet to be 0.6% and 0.4%, which is just 10% of the total building entrainment, suggesting that entrainment from other routes is significant.

INTRODUCTION

This study was prompted by complaints from the first- and second-floor tenants of an odor of diesel emissions in the building. A concern was expressed that the emissions coming from the underground railroad trains through the sidewalk exhaust grates may be entering the building ventilation system outside air intake. We decided to measure selected contaminants which are typical components of diesel exhaust (e.g., CO and NO_x) and to conduct a tracer gas test to quantify the amount of the diesel train exhaust emissions entering the building from these sidewalk grates.

The site is a high-rise office building located in the downtown area of a large city. The building is a 12-story structure and is situated directly over an underground train station. The gross area of each floor is approximately 23,000 ft². The first and second floors are predominantly office space.

The building ventilation system serving the first floor and mezzanine office areas has an outside air inlet located on the side of the building. The outside air inlet is approximately 10 ft above the sidewalk where the underground train station sidewalk exhaust grates are located. The outside air intake is a 5 ft by 12 ft screened and louvered opening which is located in a mezzanine-level mechanical room. Several ventilation systems have outside air ducts connected to this opening. We measured the airflow rate entering the outside air duct serving the first floor and mezzanine area (using a hot wire anemometer) to be 310 ft³ per minute. The second-floor area is serviced by a separate building ventilation system with outside air intakes located on the opposite side of the building.

FUME ENTRAINMENT MEASUREMENT PROTOCOL

We used a tracer gas technique to quantify the amount of train diesel emissions coming from the sidewalk exhaust grates into the building. We installed 1/4-in-diameter polyethylene tubing to inject sulfur hexafluoride gas into each of three sidewalk exhaust grates near the outside air inlet. These exhaust grates are located directly beneath and to the left and right of the outside air intake supplying air to the first-floor and mezzanine office areas. We set the total tracer gas injection rate at 5 liters per minute of 1% sulfur hexafluoride gas. We injected the tracer gas into three sidewalk exhaust grates for a period of approximately one hour, during which time we collected air samples at various indoor and outdoor locations. Figure 1 depicts the locations of the outside air intakes, sidewalk exhaust grates, and the outdoor and first-floor air sampling points. Figure 2 depicts the mezzanine level of the first floor and the outside air duct sample location in the mechanical room. Figure 3 depicts the location of the second-floor sample locations. Sample location 1 was located outdoors directly beneath the outdoor air inlet. Sample location 2 was located in the outside air duct located in the mechanical room of the first floor/mezzanine level ventilation system. Sample location 3 was located in the southwest side of the first floor and sample location 4 was located by a revolving door. Samples locations 5 and 6 were on the west side and east side of the second floor, respectively. We col-

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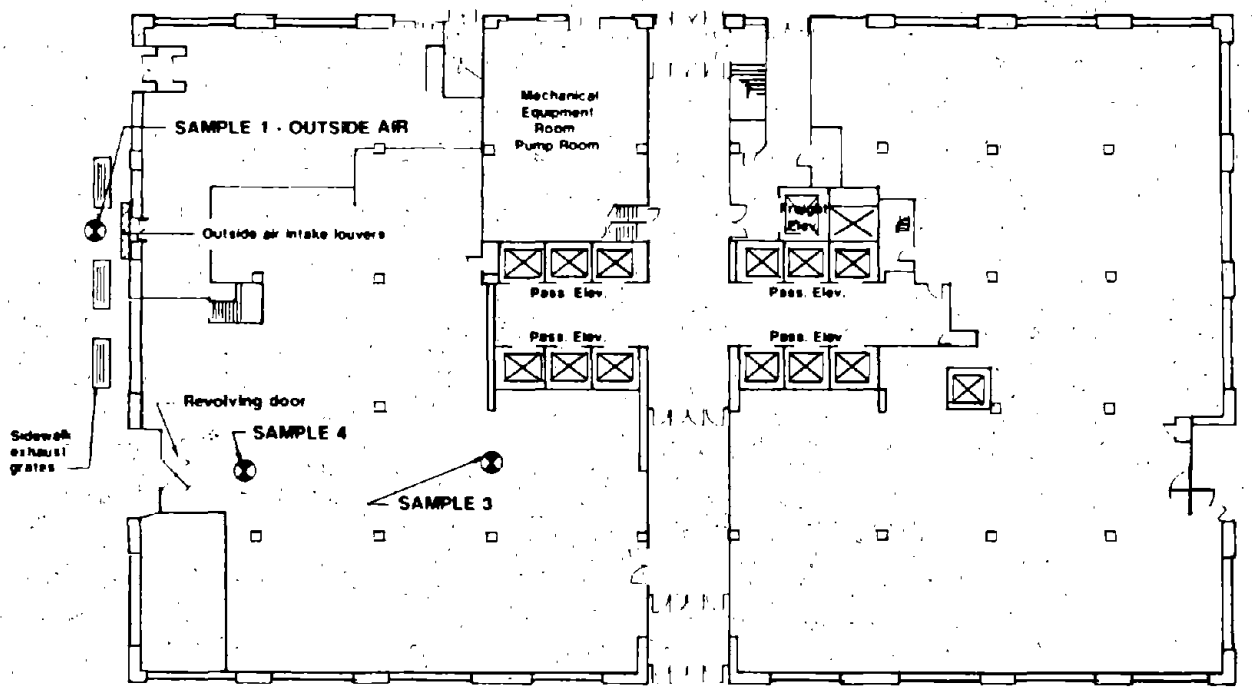

Figure 1 *Floor plan of the first floor depicting the locations of the outside air intakes, sidewalk exhaust grates, and the outdoor and first-floor air-sampling points*

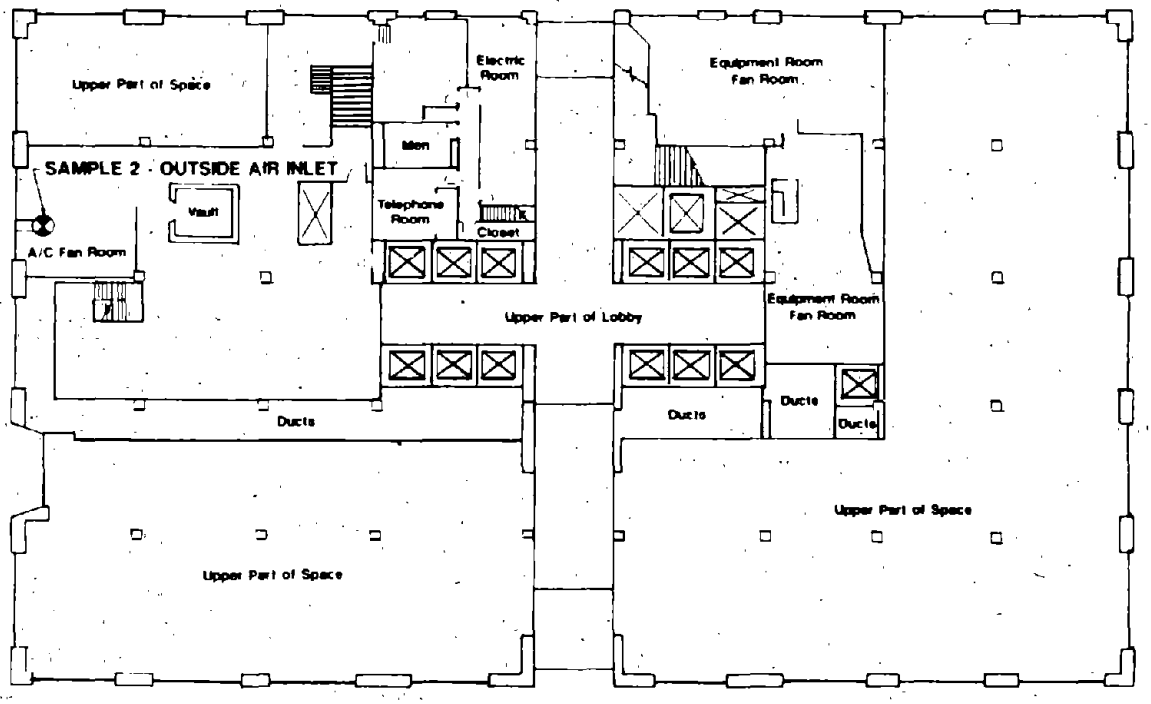

Figure 2 *Floor plan of the mezzanine level depicting the mechanical room location and the outside air duct sample location*

lected background air samples at each location before each test.

Following the start of the tracer injection we collected grab samples at each location at approximately 15-minute intervals. In addition, we installed a sample bag to continuously collect air from the outside air inlet during each test. We analyzed the samples on-site and later off-site using a gas chromatograph with an electron capture detector calibrated over a 0.1 to 50 ppb range.

We used the following formulae for calculating the entrainments observed in the outside air intake and in the indoor spaces:

Outside Air Inlet Entrainment

$$\text{Entrainment (\%)} = \frac{(C(inlet) - C(OA)) * 1E-9 * Q_v * 28.32 * 100}{Q_T} \quad (1)$$

where

$C(inlet)$ = the average tracer concentration in the outside air inlet (ppb)
$C(OA)$ = the average tracer concentration in the outside air (ppb)
Q_v = the flow rate of outside air through the inlet duct (cfm)
Q_T = the flow rate of pure tracer gas into the pollution source (lpm)

Area Entrainments

$$\text{Entrainment (\%)} = \frac{(C(t) - C(OA)) * 1E-9 * (Q_v/v) * 28.32 * 100}{(1 - e-(Q_v * t)/v)} \quad (2)$$

where

$C(t)$ = the indoor tracer concentration in the building zone at time, t, (min)
$C(OA)$ = the average tracer concentration in the outside air (ppb)
Q_v = the flow rate of outside air into the building zone (cfm)
t = time since tracer injection (min)
V = the net indoor air volume (ft^3)
Q_T = the flow rate of pure tracer gas into the pollution source (lpm)

FUME ENTRAINMENT RESULTS

We measured the outdoor concentration of carbon monoxide (CO) using an electro-chemical analyzer to range from 3 ppm to 50 ppm. We noted the highest CO concentrations (e.g., 20 to 50 ppm) during periods when there were visible emissions of train exhaust from the sidewalk grates, in particular when trains were preparing to leave from the underground station. We continuously monitored the indoor concentrations of CO in the first-floor area using another electro-chemical analyzer. The indoor concentrations steadily increased from 7 ppm to 14 ppm during the 2.5-hour measurement period. We measured nitrogen oxide (NO) and nitrogen dioxide (NO_2) using a sorbent tube sampler which we analyzed using gas chromatography (e.g., P&CAM 231). We collected air samples from 16:15 to 18:30 during a weekday evening commute period. We observed outdoor concentrations of 0.64 ppm and 0.65 ppm for NO and NO_2, respectively. We simultaneously observed indoor concentrations ranging from 0.04 ppm to 0.48 ppm for NO and 0.05 ppm to 0.25 ppm for NO2.

The results of the tracer gas measurements are summa-

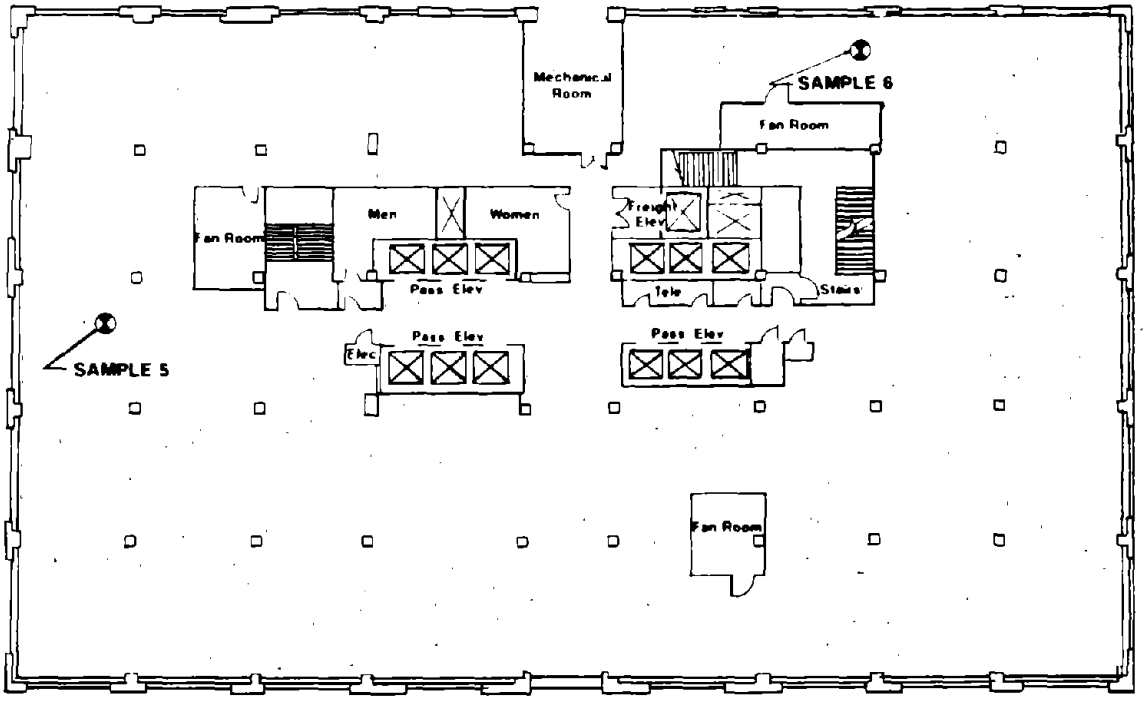

Figure 3 Floor plan of the second floor depicting the locations of the sampling points

TABLE 1

Tracer Gas Data Collected During Fume Entrainment Tests

Sample ID	Location	Time	Air Concentration (ppb)
X1	OA street	13:10	0.11
X2	OA inlet	13:07	0.11
X3	First floor south west	13:08	0.13
X4	First floor door	13:05	0.13
X5	Second floor west	13:05	0.13
X6	Second floor east	13:07	0.12
Tracer gas injection: 13:25–14:25			
A1	OA street	13:40	20.64
A2	OA inlet	13:41	113.42
A3	First floor south west	13:40	6.80
A4	First floor door	13:41	4.51
A5	Second floor west	13:41	2.38
A6	Second floor east	13:40	0.29
B1	OA street	13:55	5.37
B2	OA inlet	13.57	131.21
B3	First floor south west	13.55	13.20
B4	First floor door	13.56	10.54
B5	Second floor west	13.55	6.95
B6	Second floor east	13.56	1.31
C1	OA street	14:10	264.56
C2	OA inlet	14:11	29.00
C3	First floor south west	14:10	22.14
C4	First floor door	14:11	18.04
C5	Second floor west	14:10	6.95
C6	Second floor east	14:11	1.63
D1	OA street	14:25	8.74
D2	OA inlet	14:26	20.64
D3	First floor south west	14:25	25.51
D4	First floor door	14:26	21.76
D5	Second floor west	14:26	8.67
D6	Second floor east	14:26	1.26
E1	Mechanical Room	14:25	29.47
E2	AC-1 OA Duct-Bag	13:30–14:25	35.93

Source: Indoor Environmental Engineering, May, 1988

TABLE 2

Tracer Gas Data Collected During Fume Entrainment Test 2

Sample ID	Location	Time	Air Concentration (ppb)
N1	OA street	16:51	0.58
N2	OA inlet	16:52	0.48
N3	First floor south west	16:50	0.62
N4	First floor door	16:50	0.77
N5	Second floor west	16:48	0.13
N6	Second floor east	16:46	0.11
Tracer gas injection: 16:57–18:07			
O1	OA street	17:17	8:31
O2	OA inlet	17:18	7:34
O3	First floor south west	17:20	8.78
O4	First floor door	17:19	4.97
O5	Second floor west	17:15	4.97
O6	Second floor east	17:17	0.36
P1	OA street	17:31	27.96
P2	OA inlet	17:30	9.46
P3	First floor south west	17:34	9.67
P4	First floor door	17:33	8.50
P5	Second floor west	17:30	4.93
P6	Second floor east	17:31	3.07
Q1	OA street	17:47	3.11
Q2	OA inlet	17:48	14.84
Q3	First floor south west	17:51	11.77
Q4	First floor door	17:50	11.03
Q5	Second floor west	17:47	7.05
Q6	Second floor east	17:48	0.50
R1	OA street	18:07	1.49
R2	OA inlet	18:04	69.19
R3	First floor south west	18:07	14.42
R4	First floor door	18:07	15.09
R5	Second floor west	18:10	10.93
R6	Second floor east	18:11	0.83
S1	AC-1 SA	18:05	17.08
S2	AC-1 SA	18:06	17.49
S7	AC-1 OA Duct-Bag	17:15–18:10	24.57

Source: Indoor Environmental Engineering, May, 1988

rized in Tables 1 and 2. These air concentrations are also depicted in the concentration vs. time plots presented in Figures 4-7. The results of the entrainment calculations are presented in Table 3. We calculated the outside air inlet entrainment percentage as the ratio of the measured flux of tracer gas entering the outside air inlet to the measured flux of tracer released into the sidewalk exhaust grates. We computed the outside air flux from the measured outside airflow rate of 310 cfm and the average tracer gas concentrations measured in the outside air duct. We calculated the three building zone entrainments as the ratio of the computed flux of tracer gas entering each building zone to the measured flux of tracer released into the sidewalk exhaust grates. We computed the flux of tracer entering each building zone from the measured indoor tracer gas concentrations, the estimated indoor air space volumes, and assuming an effective building air exchange rate of one air change per hour in each of the three building zones. We calculated the total building entrainment as the sum of the three computed zone entrainment rates (i.e., first floor southwest, second floor east, and second floor west).

We computed the total entrainment of the diesel emissions from the sidewalk exhaust grates into the building to be 5.8% for Test 1 and 4.5% for Test 2. The majority of the entrained diesel emissions were traced to the the first-floor area, where 4.2% and 2.6% of the released tracer gas were observed for Tests 1 and 2, respectively. The average entrainment of diesel emissions into the building through the outside air inlet was measured to be 0.6% and 0.4%, respectively.

DISCUSSION AND RECOMMENDATIONS

We used a tracer gas technique to determine the total entrainment of diesel exhaust emissions from sidewalk grates to be 5.8% and 4.5% for a pair of consecutive tests. This represents a substantial amount of entrainment and is consistent with the proximity of the sidewalk exhaust grates to the building. Most of the entrained tracer gas was observed to enter the first-floor office area. The amount of entrainment occurring through the outside air inlet was computed to be just 0.6% and 0.4% of the total observed entrainment. Other potential sources of entrainment of diesel emissions from the sidewalk exhaust grates are:

1) Air leakage through the doors.
2) Air leakage through the building expansion joint.
3) Air leakage in the return air ducts of the mechanical room located on the mezzanine level.

We observed that the tracer concentration in the mezzanine mechanical room at the end of Test 1 was significant

TABLE 3

Sidewalk Diesel Emission Entrainment Tracer Gas Test Results

Test	Injection Time	Sidewalk Exhaust Fume Entrainment (%)[a] Outside Air Duct	1st Floor	2nd Floor-W	2nd Floor-E	Total
1	13:25–14:25	0.6	4.2	1.4	0.2	5.8
2	16:57–18:07	0.4	2.6	1.8	0.1	4.5

a.) The outside air inlet entrainment percentage is calculated as the ratio of the measured flux of tracer gas entering the outside air inlet ot the measured flux of tracer released into the sidewalk exhaust grates. The outside air flux was computed from the measured outside air flow rate of 310 cfm and the average tracer gas concentrations measured in the outside air duct.

The building zone entrainments are calculated as the ratio of the computed flux of tracer gas entering the building zone to the measured flux of tracer released into the sidewalk exhaust grates. The flux of tracer entering each building zone was computed from the measured indoor tracer gas concentrations, the estimated indoor air space volumes, and assuming an effective building air exchange rate of one air change per hour in each of the three building zones.

The total building entrainment was computed as the sum of the three computed zone entrainment rates (i.e. 1st Floor + 2nd Floor West + 2nd Floor East).

Source: Indoor Environmental Engineering, May, 1988

and thus any leakage in the return air duct system would be a significant source of diesel emissions into the building.

The recommended mitigation for this type of fume entrainment is elimination of the source. In this case, eliminating the source may be as simple as sealing off the sidewalk exhaust grates and providing an alternate means of safely exhausting diesel emissions from the train station. Another option available should elimination of the source not be feasible is building pressurization with an air scrubber designed to remove the diesel emissions from the outside air.

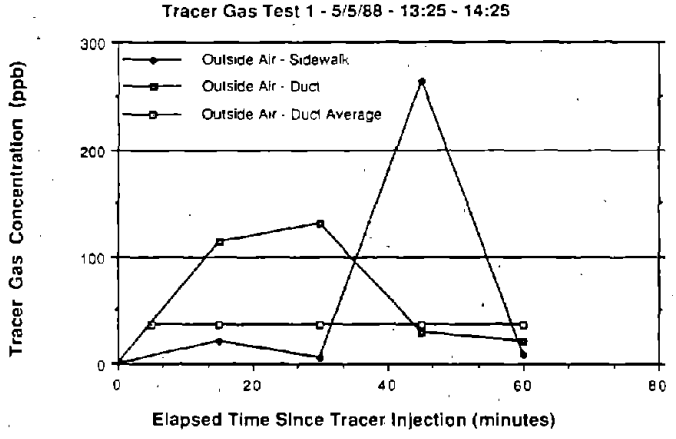

Figure 4 Tracer gas outdoor concentrations during fume entrainment Test 1

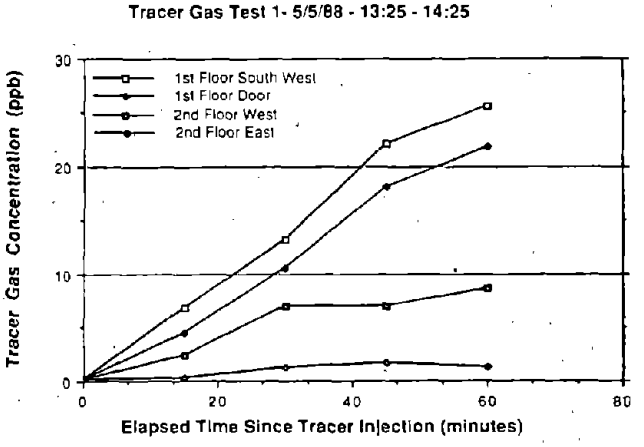

Figure 5 Tracer gas indoor concentrations during fume entrainment Test 1

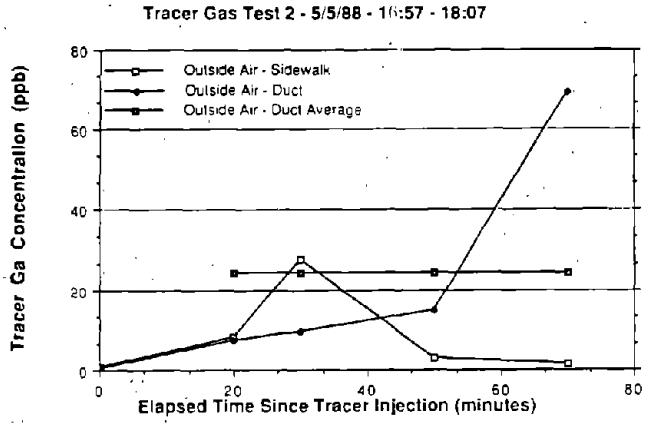

Figure 6 Tracer gas outdoor concentrations during fume entrainment Test 2

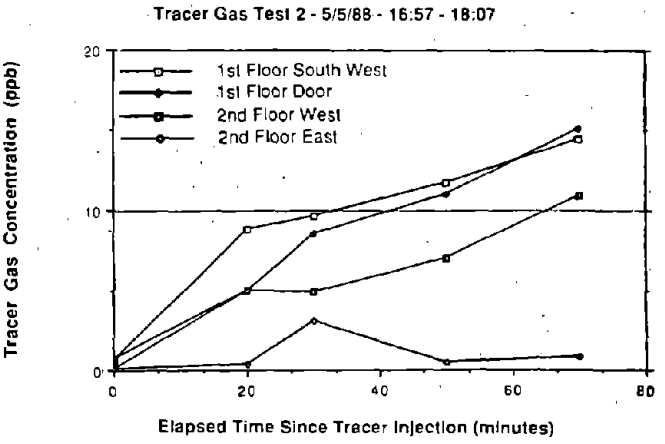

Figure 7 Tracer gas indoor concentrations during fume entrainment Test 2

OCCUPANT-CONTROLLED RESIDENTIAL VENTILATION

L.E. Alevantis, P.E. *ASHRAE Associate Member*
J.R. Girman

ABSTRACT

The effects of opening windows on the ventilation rates of two detached houses and a two-story condominium were studied. The scenarios studied under various wind conditions included, when possible, opening windows on the windward side, the leeward side, both the windward and leeward sides, and on the two other sides not in the direction of the prevailing wind. Two window settings, either 3 in or wide open, were employed in each scenario. In some cases, opening windows increased ventilation by as little as 20%, while in other cases residential ventilation rates were increased by as much as 11 times the original rate. Use of a kitchen range hood nearly doubled the ventilation rate in two residences, while opening the main garage door increased garage ventilation rates from as little as 4 times to as much as 25 times the initial rate.

INTRODUCTION

Adequate ventilation of any enclosed space is essential for good indoor air quality and for thermal comfort. New energy-efficient, low-air-leakage houses located in extreme weather areas are usually mechanically ventilated, since the infiltration rates of these houses are not sufficient for moisture control or acceptable indoor air quality. However, the majority of the houses in the United States are ventilated by infiltration. While infiltration rates of many groups of houses have been measured and reported in the past (ASHRAE 1985), little quantitative information exists on the effect of opening windows, despite the fact that it is the principal means by which occupants can increase ventilation when needed.

Such information would have many uses. For example, many consumer products contain chemicals which can, under certain conditions of use, create a health hazard to users and to other occupants of a residence. Quite often these products are labeled with a warning to use with "adequate ventilation."

Because information regarding residential ventilation rates with windows open under different conditions is lacking, what constitutes adequate ventilation is not clear to the consumer and may not even be known to those responsible for the warning label, i.e., is adequate ventilation provided by a large, drafty house; a house with a window open under windless conditions; or a garage with the main door open and a fan blowing to exhaust any pollutants emitted from the product? (The U.S. Consumer Product Safety Commission warning label requirement for products containing methylene chloride is an exception to this [*Federal Register* 1986]. The label for these products specifies that the product should be used outdoors if possible, but if it must be used indoors that all windows and doors should be opened or other means used to ensure that ventilation is provided.) Quantitative data about the effects of opening windows on residential ventilation could be used in models to estimate the pollutant concentrations produced under many conditions of use and thereby provide specific information regarding the applicability of different ventilation strategies to the public.

Kvisgard et al. (1985), using constant-concentration tracer gas techniques in 25 Danish occupied dwellings, monitored winter ventilation and infiltration rates over a period of one week. Their results indicate a mean increase in ventilation rates due to occupant behavior of 2.6 times in naturally ventilated houses and of 5.7 times in mechanically ventilated houses. The infiltration rates ranged from 0.20 ach to 0.40 ach, whereas the ventilation rates (including infiltration) ranged from 0.20 ach to 1.56 ach.

A large-scale study of the behavior of house inhabitants (AIVC 1988) conducted in five European countries, which examined energy losses due to winter ventilation, concluded that ventilation, as controlled by the occupant, is related to the type of room in which it occurs, to the weather conditions, and to the design characteristics of the dwelling and its heating system.

A study by De Gids and Van Schijndel (1979) conducted in a European apartment indicated a maximum increase of 4.3 in the apartment's ventilation rate when three windward windows were opened. A maximum increase of 1.5 was observed when two leeward windows of the same apartment were opened.

The results of a survey of 332 California residences conducted through the mail by the California Department of Health Services (CDHS)*, part of which are shown in Figure 1, indicated that window-opening behavior exhibits a strong seasonal dependence. In addition, this survey found that 75.6% of the residences surveyed were single-family houses, and 75.8% of the residences had a kitchen fan.

Another survey of 661 California mobile home occupants, also conducted through the mail by the CDHS*, provided information about occupant control of ventilation. The results shown in Figure 2 suggest that opening windows depends on the type of room in which it occurs as well as on the season. The data also indicated that 23.0% of the mobile home occupants used their kitchen fan 1 to 10 minutes per week, and that 20.2% used their kitchen fan 21 to 40 minutes per week.

This paper reports on a study of the effect of opening windows on residential ventilation rates. Among the factors studied were the effects of wind speed, the amount the window was opened, the wind direction in relation to the window, and the number of windows opened. In addition, ventilation measurements were taken in the garages at each of these residences since limited information exists regarding venti-

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lation rates in garages (e.g., Hodgson and Girman 1987) despite the fact that they can be areas of high exposure to pollutants because of storage of solvents or because of hobbyists' activities.

DESCRIPTION OF THE STUDY

Three residences were studied--two detached houses (Residences 1 and 2) and one condominium (Residence 3). The scenarios employed under various wind conditions included, when possible, opening windows on the windward side, the leeward side, both the windward and leeward sides, and on the two other sides not in the direction of the prevailing wind. Two window settings, 3 in and wide open, were employed in each scenario.

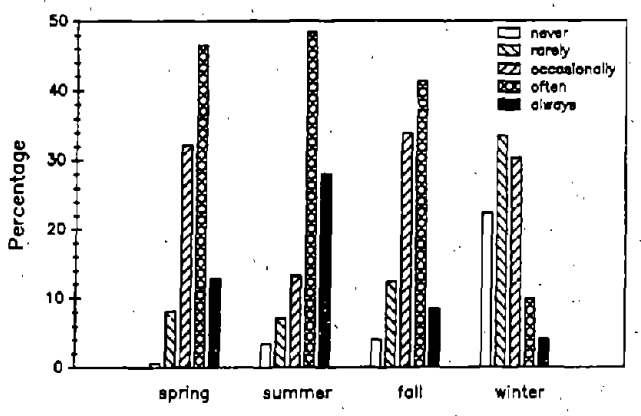

Figure 1 Occurrence of open windows and doors in a sample of 332 occupied California residences according to season

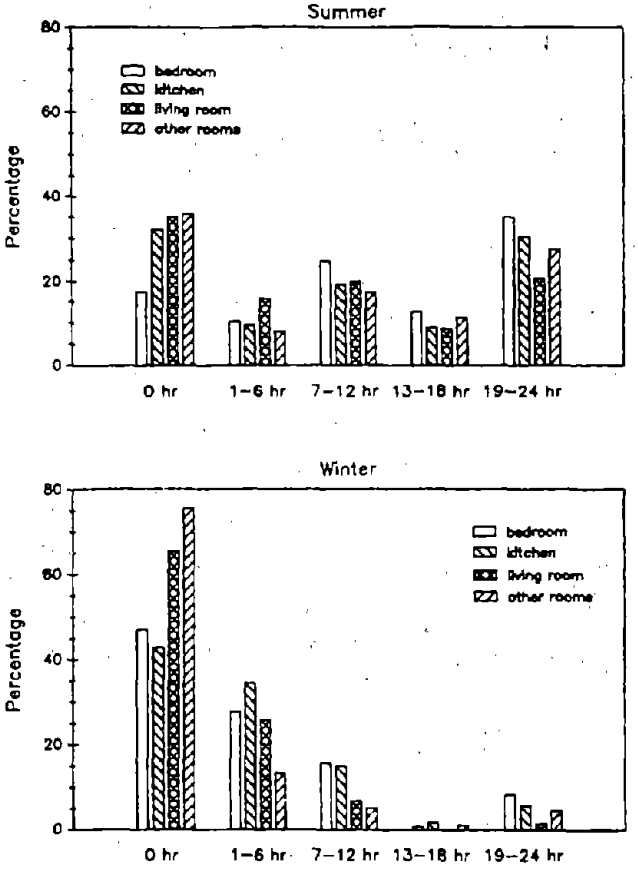

Figure 2 Duration of open windows in a sample of 661 occupied California mobile homes according to season and type of room

Natural infiltration rates were measured at Residences 1 and 3 under various wind conditions. The effects of the range hood operation on the ventilation rates were also studied. In addition, the effect of the furnace fan on air mixing at the two-story condominium (Residence 3) was examined. Finally, garage ventilation rates with the main door open and closed were measured in all three residences.

Air change rates were determined after sulfur hexafluoride (SF_6) was released upstream of the furnace fan in Residences 1 and 2. In Residence 3 several injections of SF_6 were made throughout the condominium and small portable fans were used for mixing. After allowing 30 to 40 minutes for mixing in all three residences, the fan(s) were turned off, and the SF_6 decay was monitored in several locations by using a computer-controlled, multi-location sampling technique. This technique has been described in detail elsewhere (Alevantis 1989). Range hood flows were determined by making multi-point traverses across the range hood inlets using a hot-wire anemometer.

DESCRIPTION OF THE RESIDENCES

Residence 1 (see Figure 3) is a one-story, 1321 ft², two-year-old, three-bedroom house with no outside sheltering on the southwestern side and fencing on the other three sides. This house has horizontal sliding windows and is served by a forced-air heating and cooling system. The average outdoor temperature during the study was 82°F and the average indoor temperature was 74°F.

Residence 2 (see Figures 4a and 4b) is a two-story, 1326 ft², approximately 60-year-old, two-bedroom house with trees sheltering the southwestern, northeastern, and northwestern

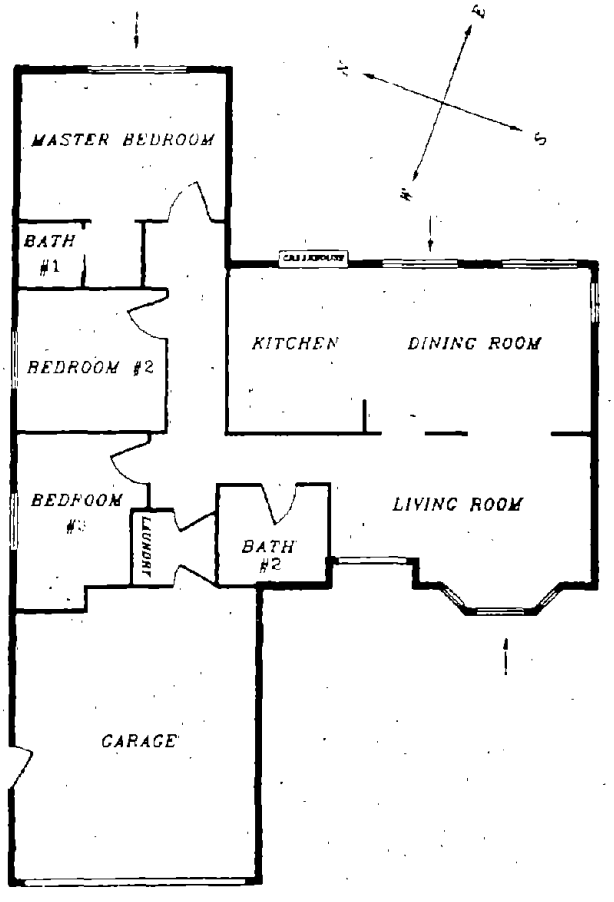

Figure 3 Floor plan of Residence 1

sides, and fencing on the northwestern and southeastern sides. The ground floor consists of a garage and a small, one-bedroom rental unit, while the main two-bedroom house occupies the entire second story. This house principally has double-hung windows and few casement windows. The main house is served by a forced-air heating system, while the rental unit is served by a gas-fired convection wall furnace. During the study the average indoor temperature was 68°F and the average outdoor temperature was 58°F.

Residence 3 (see Figures 5a and 5b) is a two-story, 872 ft², approximately seven-year-old condominium with adjacent units located on the southwestern and northeastern sides. This residence has horizontal sliding windows and a forced-air heating system serves both floors. The average indoor temperature during the study was 68°F; outdoor temperature was not continuously monitored but was estimated to be 55°F.

RESULTS AND DISCUSSION

In Residences 1 and 3, several infiltration rates were obtained under different wind conditions with all the windows closed. Infiltration rates of these two residences were then plotted against wind speed (see Figures 6 and 7) assuming a linear relation (ASHRAE 1985). The increase in a residence's ventilation rate due to opening window(s) is defined here as the ratio of the ventilation rate with the window(s) open to the infiltration rate under similar wind conditions with all the windows closed. In Residence 2, since wind conditions were largely invariant, an average infiltration rate was calculated irrespective of wind speed.

Residence 1

The effect of wind speed (4.8 to 25 mph) on infiltration with all windows closed is shown in Table 1 (Cases 1 through 4) and Figure 6. Wind speed increased the house infiltration rates monotonically from as little as 4.1 times (Case 2) to as much as 8.7 times (Case 4) when compared to the base case (Case 1).

Opening windows (Cases 5 through 8) resulted in an increase in the house's ventilation rate from as little as 4.6 times (Case 6: one windward and two leeward windows open 3 in, wind speed 11 mph) to as much as 7.7 times (Case 5: one windward window open 3 in; wind speed 4.8 mph) over the house's infiltration rate with all the windows closed under similar wind conditions. Operation of the kitchen range hood doubled the ventilation rate (Cases 9 and 10).

The garage ventilation rates are shown in Table 2. An average ventilation increase of 5.0 times (average increase of Cases 4 and 5) was observed when the garage door, located on the windward side of the house, was opened.

Residence 2

At this house, since wind speed was fairly constant, as seen in Table 3 (Cases 1 through 5), the average infiltration rate of these cases was the basis for comparison with the ventilation rates when windows were opened. The house ventilation rate was increased from as little as 1.2 times (Cases 6 and 13: one side window open 3 in; Case 18: one side window wide open; and Case 8: one leeward window open 3 in) to as much as 7.5 times (Case 17: one small casement

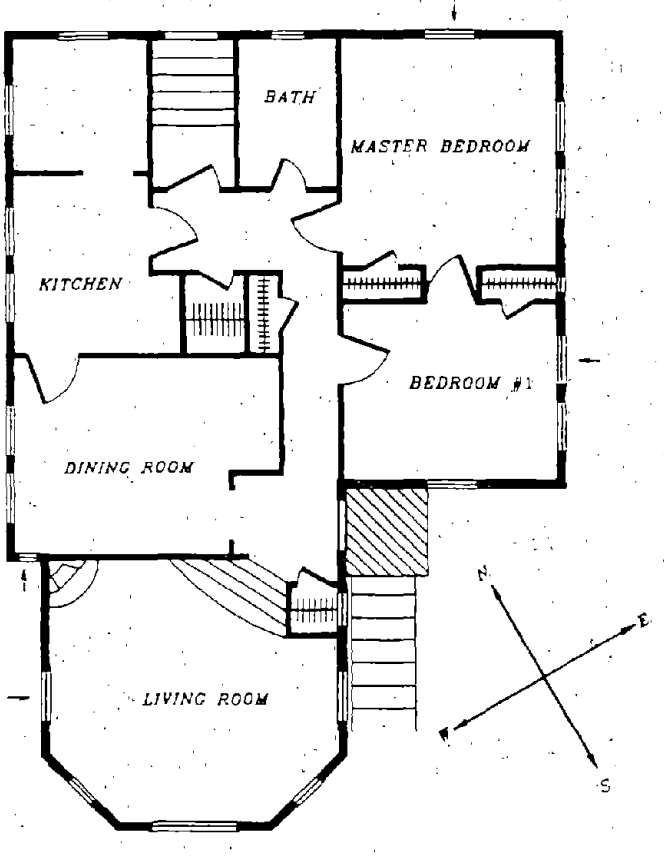

Figure 4a Second-story floor plan of Residence 2

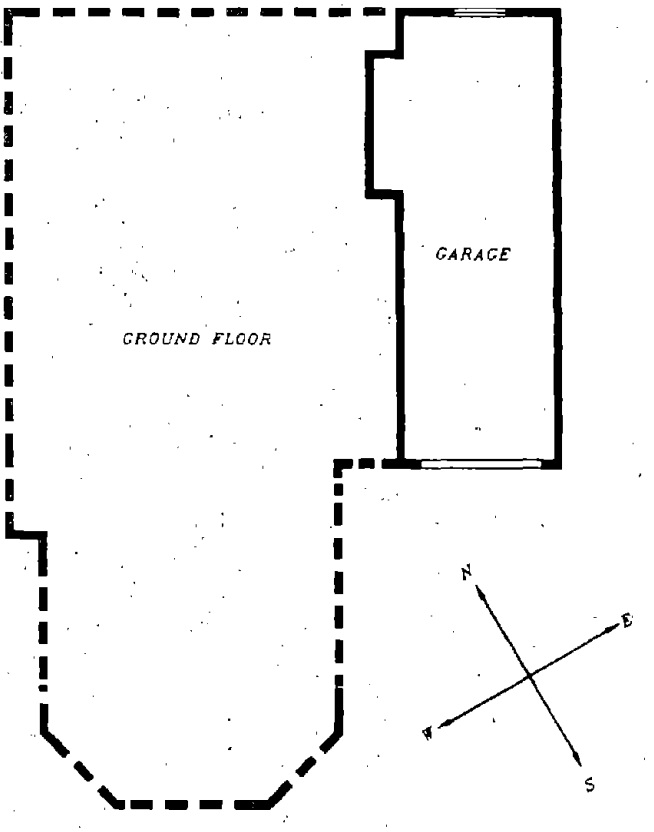

Figure 4b First-story floor plan of Residence 2

windward window and one sliding leeward window wide open). Operating the kitchen range hood (Cases 20 and 21) did not increase the ventilation rate measurably, presumably because of the low flow of the fan (60 cfm or 102 m³/h).

The garage ventilation rates are shown in Table 4 with the main garage and sliding doors open and closed (these doors are located on the windward and leeward sides, respectively), and with a portable window fan (22 in wide by 22 in tall) on and off. An eightfold increase in the ventilation rate was observed (Case 3) when the main garage door was opened. A more than sixtyfold increase was measured (Case 2) when both the garage door and the sliding door (located across from the garage door) were opened, resulting in a drafty but not windy indoor environment. The portable fan doubled the garage ventilation rate (Case 6: main garage door open; sliding door closed) when compared to Case 3 (main and sliding garage doors closed; no fans running). However, the fan did not result in any ventilation rate increase when both garage doors were open (Case 5).

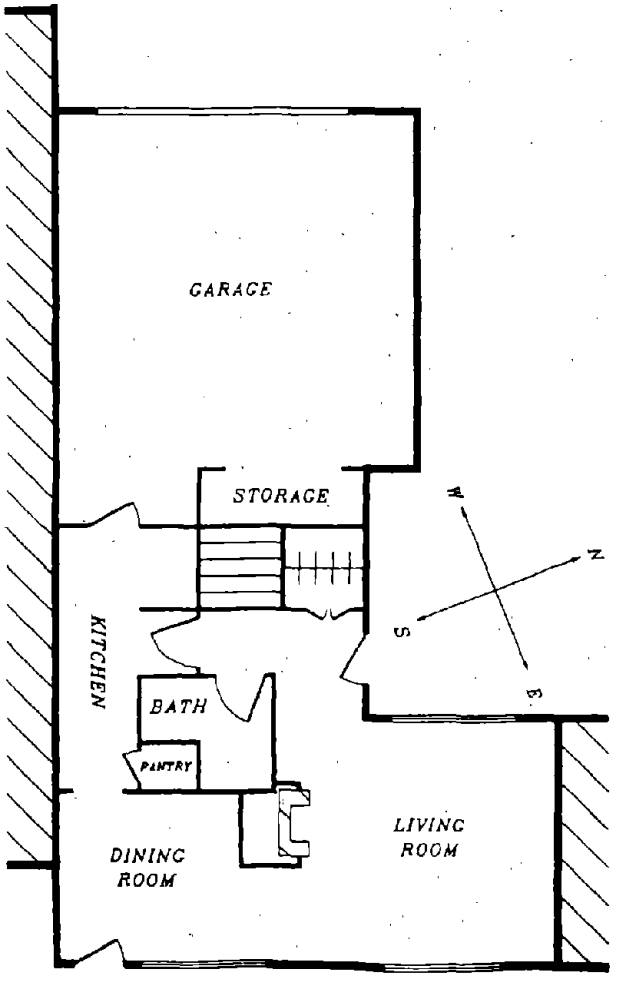

Figure 5a First-story floor plan of Residence 3

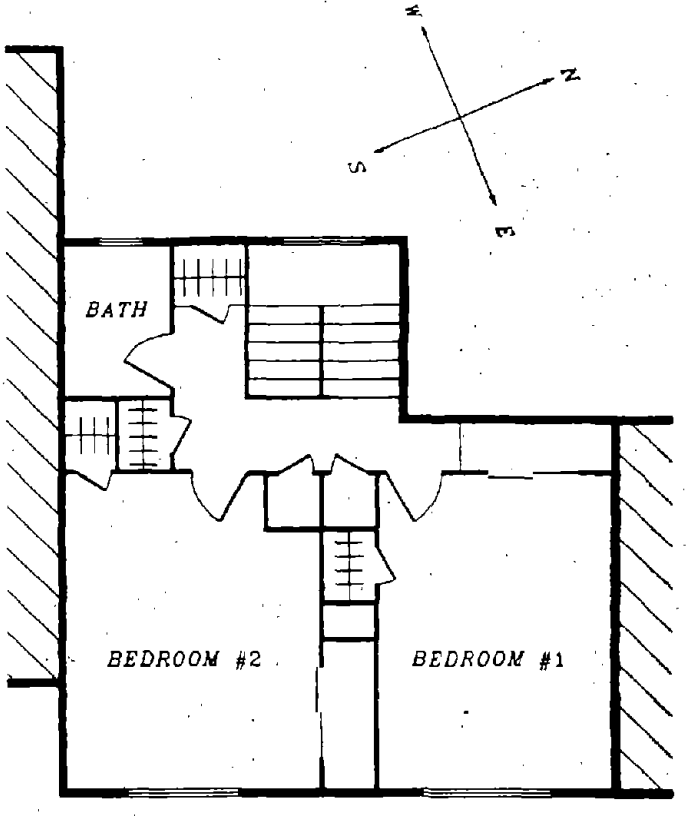

Figure 5b Second-story floor plan of Residence 3

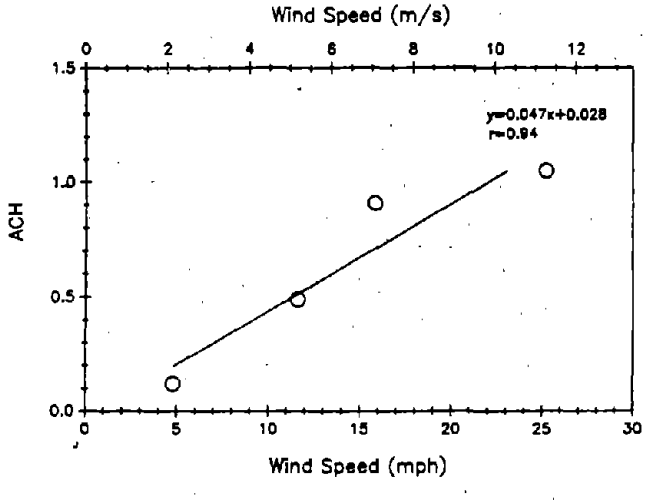

Figure 6 Effect of wind speed on natural infiltration (all windows closed) of Residence 1. Line is least-squares, linear fit.

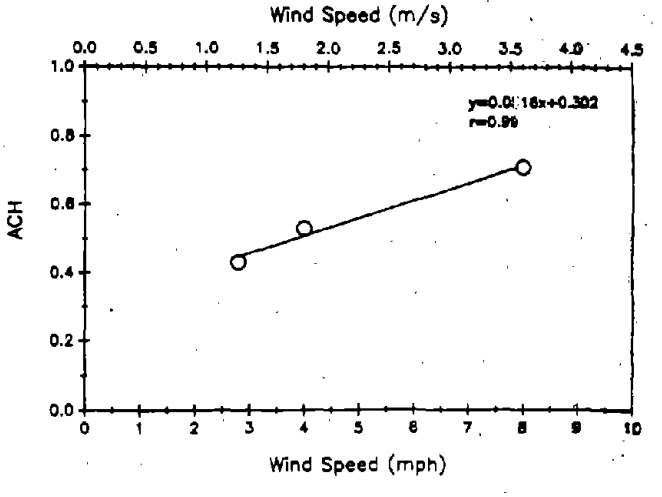

Figure 7 Effect of wind speed on natural infiltration (all windows closed) of Residence 3. Line is least-squares, linear fit.

TABLE 1

Residence 1 — Air Change Rates

Case No.	Living Room[a] (WSW)	Dining Room[b] (ENE)	Master Bdrm[c] (ENE)	Range Hood	Wind Speed (mph)	Wind Dir.	Avg. ACH	ACH / ACH_{inf}[d]
			A. Base Cases: All Fans Off, All Windows Closed					
1	closed	closed	closed	off	4.8	SW	0.12	—
2	closed	closed	closed	off	12.0	WSW	0.49	—
3	closed	closed	closed	off	16.0	WSW	0.91	—
4	closed	closed	closed	off	25.	WSW	1.0	—
			B. Effect of Open Windows (all fans off)					
5	3 in	closed	closed	off	4.8	SW	0.92	7.7
6	3 in	3 in	3 in	off	11.	SW	2.3	4.6
7	12 in[e]	closed	closed	off	11.	WSW	3.1	6.6
8	12 in[e]	12 in[e]	12 in[e]	off	11.	W	2.8[f]	—
			C. Effect of Range Hood (Hi: 128 CFM, Lo: 115 CFM) (all windows closed, all other fans off)					
9	closed	closed	closed	hi	12.	WSW	1.0	1.9
10	closed	closed	closed	lo	12.	WSW	1.0	2.0

[a]window height is 57 in
[b]window height is 77 in
[c]window height is 38 in
[d]ACH_{inf} is the infiltration rate under the same wind conditions with the furnace fan off, and all windows closed (see Figure 6)
[e]wide open
[f]air mixing was poor

TABLE 2

Residence — Garage Ventilation Rates

Case No.	Garage Door (WSW)	Wind Speed (mph)	Wind Direction	Average ACH	ACH / ACH_{inf}[a]
1	closed	12.	W	9.9	—
2	closed	13.	WSW	15.	—
3	closed	13.	WSW	14.	—
4	open	12.	W	79.	6.0
5	open	14.	W	53.	4.1

[a]ACH_{inf} is the average garage infiltration rate of Cases 1 through 3 with the door closed

Residence 3 (Figure 5)

In Residence 3, the two-story condominium, infiltration rates (Tables 5 and 6: Cases 1 through 5) were obtained under two air-mixing conditions: with the furnace fan off and on. The local air change rates for Case 5 (when the furnace fan was on) indicate good mixing. In contrast, mixing was poor when the furnace fan was not running and the wind speed was more than 4.0 mph (Cases 3 and 4). The occupant of this condominium was dissatisfied with the performance of the furnace because the upstairs rooms were always too hot in the winter and the downstairs rooms were uncomfortably cold. The furnace fan operates only when heat is called for. Wind speed and wind direction increased the infiltration rates from no change at all to as much as 1.6 times (Cases 1 through 4). The effect of wind on infiltration is shown in Figure 7.

Opening windows caused the ventilation to increase from as little as 4.1 times (Case 11: one windward window wide open; wind speed 4.6 mph) to as much as 11 times (Case 8: four leeward and one windward windows wide open; wind speed 4.0 mph). An increase of 4.2 (Case 9: wind speed 3.8 mph) was observed when four leeward windows were opened. Use of the range hood nearly doubled the ventilation rate (Case 12).

The effects of operating a portable fan and of opening the garage door (located on the windward side) on the garage infiltration and ventilation rates are shown in Table 7. An average increase of 21 (Cases 4 and 5) in the garage ventilation rate occurred when the garage door was opened. The portable fan (when the garage door was closed—Case 3) increased the garage ventilation rate by 40%.

CONCLUSIONS

The following conclusions can be drawn from Figure 8 (which summarizes the window-opening data), Table 8 (which summarizes the garage door-opening data), Table 9 (which summarizes the kitchen hood data for the three residences studied), and Figure 6 (which shows the effect of wind on the infiltration rates of Residence 1):

1. In the three residences studied, wind conditions (both speed and direction) were observed to cause wide variation in a residence's natural infiltration rate with all the windows closed. The maximum natural infiltration rate could be as much as 8.7 times the minimum rate at a residence under the conditions experienced during the study.
2. Wind conditions can also cause wide variation in the ventilation rate when windows are open. Opening windows on both the windward and leeward sides of a residence at wind speeds below 5 mph can cause the ventilation rate to increase from as little as 4.5 times to as much as 11 times the residence's natural infiltration rate at the same wind conditions with all the windows closed. At wind speeds between 5 mph and 11 mph, an increase in a res-

TABLE 3

Residence 2 — Air Change Rates

Case No.	Living Room[a] (NW)	Dining Room[b]	Master Bdrm[c] (NE)	Bedroom 1[d] (SE)	Kitchen[e] (NW)	Range Hood	Wind Spd. (mph)	Wind Dir.	Avg. ACH	ACH / ACH_{inf}[f]
				A. Base Cases: All Fans Off, All Windows Closed						
1	closed	closed	closed	closed	closed	off	1.9	SSE	0.31	—
2	closed	closed	closed	closed	closed	off	2.3	ESE	0.44	—
3	closed	closed	closed	closed	closed	off	2.2	SW	0.40	—
4	closed	closed	closed	closed	closed	off	2.2	SW	0.30	—
5	closed	closed	closed	closed	closed	off	2.2	SW	0.38	—
				B. Effect of Open Windows (all fans off)						
6	3 in	closed	closed	closed	closed	off	2.4	WSW	0.43	1.2
7	3 in	closed	3 in	closed	closed	off	2.4	WSW	0.75	2.0
8	closed	closed	3 in	closed	closed	off	2.8	SW	0.43	1.2
9	23 in[g]	closed	closed	closed	closed	off	2.2	WSW	0.53	1.4
10	23 in[g]	closed	23 in[g]	closed	closed	off	2.2	WSW	1.87	5.0
11	closed	closed	23 in[g]	closed	closed	off	3.5	SW	0.91	2.4
12	closed	closed	23 in[g]	closed	closed	off	2.3	WSW	0.68	1.8
13	closed	NW 3 in	closed	closed	closed	off	2.5	SSW	0.43	1.2
14	closed	NW 3 in	closed	3 in	closed	off	2.5	SSW	0.67	1.8
15	closed	NW 15 in[g]	closed	22 in[g]	closed	off	1.9	SW	1.79	4.8
16	closed	SW 8in[g]	closed	closed	closed	off	2.2	SW	0.74	2.0
17	closed	SW 8 in[g]	23 in[g]	closed	closed	off	3.3	WSW	2.8	7.5
18	closed	closed	closed	closed	29 in[g]	off	3.7	S	0.46	1.2
19	closed	closed	closed	22 in[g]	29 in[g]	off	3.7	SW	1.3	3.5
				C. Effect of Range Hood (60 CFM) (all windows closed, all other fans off)						
20	closed	closed	closed	closed	closed	on	3.0	SW	0.41	1.1
21	closed	closed	closed	closed	closed	on	3.8	SE	0.46	1.2

[a]window height is 33 in
[b]height of NW window is 58 in; height of SW window is 56 in
[c]window height is 41 in
[d]window height is 29 in
[e]window height is 16 in
[f]ACH_{inf} is the average house infiltration rate of Cases 3 through 5 with all windows closed and all fans off.
[g]wide open

TABLE 4

Residence 2 — Garage Ventilation Rates

Case No.	Garage Door (SW)	Sliding Door (NE)	Portable Fan	Wind Speed (mph)	Wind Direction	Average ACH	ACH / ACH_{inf}[a]
1	closed	closed	off	1.8	WSW	0.66	—
2	open	open	off	2.6	S	40.	6.1
3	open	closed	off	2.1	E	5.3	8.0
4	closed	closed	on	2.0	SE	0.81	1.2
5	open	open	on	2.6	ENE	37.	56.
6	open	closed	on	2.0	SE	11.	17.

[a]ACH_{inf} is the garage infiltration rate with all doors closed (Case 1)

idence's ventilation rate of up to 4.6 times over a residence's natural infiltration rate (under the same wind conditions and with all windows closed) can be expected when windows in both the windward and leeward sides are opened. Apparently, this occurs because infiltration increases at a faster rate with increasing wind speed than does ventilation due to opening windows under the same wind conditions.

3. Opening windows that are not in the direction of the prevailing wind is not as effective in increasing house ventilation as is opening windows on the windward and leeward sides. However, a modest ventilation increase of at least 20% can be expected.
4. Fully opening several leeward windows can result in approximately the same ventilation rate increase as does fully opening one windward window, or opening all windward and leeward windows 3 in.
5. Opening a window even 3 in on each of the windward and leeward sides of a house can be expected to increase the ventilation rate by at least 80%.
6. Operation of a modern range hood can double the house ventilation rate (when all the windows are closed).
7. Opening the main garage door can cause the garage ventilation rate to increase by at least 4 times over the garage's natural infiltration rate with the door closed.

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TABLE 5

Residence 3 — Air Change Rates

Case No.	Dining Room[a] (ESE)	Living Room[a] (ESE)	Stair-way[b] (WNW)	Master Bedrm[c] (ESE)	Bedroom 1[c] (ESE)	Range Hood	Furn. fan	Wind Spd. (mph)	Wind Dir.	Avg. ACH	ACH / ACH$_{inf}$[d]
					A. Base Cases: All Fans Off, All Windows Closed						
1	closed	closed	closed	closed	closed	off	off	2.8	SW	0.43	—
2	closed	closed	closed	closed	closed	off	off	4.0	WNW	0.53	—
3	closed	closed	closed	closed	closed	off	off	4.4	S	0.40	—
4	closed	closed	closed	closed	closed	off	off	8.0	NNW	0.71	—
					B. Air Mixing Effect of Furnace Fan (all windows closed)						
5	closed	closed	closed	closed	closed	off	on	4.0	NNW	0.47	—
					C. Effect of Open Windows (all fans off)						
6	3 in	3 in	3 in	3 in	3 in	off	off	2.9	NW	2.0	4.5
7	3 in	3 in	closed	3 in	3 in	off	off	6.2	SSE	1.7	—[e]
8	33 in[f]	33 in[f]	21 in[f]	33 in[f]	33 in[f]	off	off	4.0	NW	5.5	11.
9	33 in[f]	33 in[f]	closed	33 in[f]	33 in[f]	off	off	3.8	NNW	2.1	4.2
10	33 in[f]	33 in[f]	closed	33 in[f]	33 in[f]	off	off	7.0	S	4.9	—[e]
11	closed	closed	21 in[f]	closed	closed	off	off	4.6	W	2.2	4.1
					D. Effect of Range Hood (178 CFM) (all windows closed, all other fans off)						
12	closed	closed	closed	closed	closed	high	off	3.7	NW	0.95	1.9

[a]window height is 47 in
[b]window height is 35 in
[c]window height is 39 in
[d]ACH$_{inf}$ is the house infiltration rate under the same wind conditions with all windows closed and all fans off (see Figure 7)
[e]insufficient points for estimating infiltration under existing wind conditions
[f]wide open

TABLE 6

Residence 3 — Local Air Change Rates

Case No.	Injection Location	Dining Room	Living Room	Stair-way	Master Bedrm	Bedroom 1	Average ACH
			A. Base Cases: All Fans Off, All Windows Closed				
1	space	0.43	0.44	0.45	0.44	0.39	0.43
2	space	0.52	0.53	0.55	0.55	0.50	0.53
3	space	0.46	0.44	0.42	0.41	0.28	0.40
4	space	0.85	0.79	0.74	0.59	0.60	0.71
			B. Air-Mixing Effect of Furnace Fan (all windows closed)				
5	space	0.46	0.47	0.47	0.49	0.47	0.47

TABLE 7

Residence 3 — Garage Ventilation Rates

Case No.	Garage Door (WNW)	Portable Fans	Wind Speed (mph)	Wind Direction	Average ACH	ACH / ACH$_{inf}$[a]
1	closed	off	3.0	WNW	0.90	—
2	closed	off	5.5	N	1.4	—
3	closed	on	5.7	N	1.9	1.4
4	open	off	3.7	NW	22.	25.
5	open	off	3.2	NNW	15.	17.

[a]ACH$_{inf}$ is the average garage infiltration rate of Cases 1 and 2 with door closed and fan off.

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TABLE 8

Summary of Garage Door Opening Data

No.	Garage door's location relative to wind	Wind Speed (mph)	ACH increase
1.	Windward	12.	6.0
2.	Windward	14.	4.1
3.	Side[a]	2.1	8.0
4.	Windward	3.7	25.
5.	Windward	3.2	17.

[a]Not in the prevailing wind's direction

TABLE 9

Summary of Kitchen Hood Data

No.	Airflow (cfm)	ACH increase
1.	128	1.9
2.	115	2.0
3.	60	1.1
4.	178	1.9

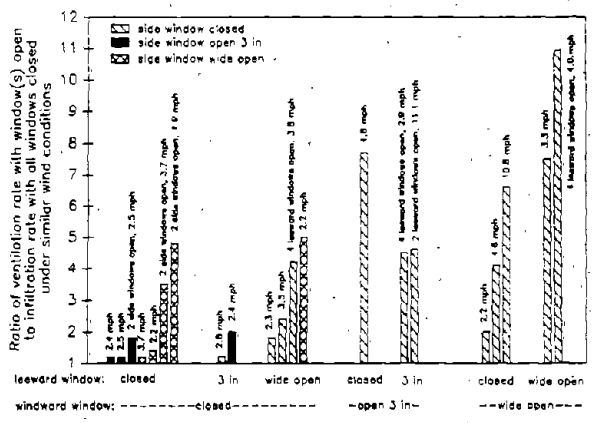

Figure 8 Summary of the ventilation data of the three residences studied

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Investigations/Evaluations/Calculations

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FINDINGS OF THE ONTARIO INTER-MINISTERIAL COMMITTEE ON INDOOR AIR QUALITY

G.S. Rajhans, P.Eng., CIH, ROH

INTRODUCTION

The Ontario Ministry of Labour (MOL) and Ministry of Government Services (MGS) have investigated more than 2000 indoor air complaints since 1976. All complaints were reported in sealed window buildings equipped with central heating, ventilating, and air-conditioning systems (HVAC). In many cases, the causes of the symptoms could not be found.

The concern about indoor air quality (IAQ) is shared by many ministries. It was recognized that IAQ complaints would likely persist in the future and that the Ontario government needs a guideline for defining indoor air parameters and a uniform protocol for investigating "sick building" complaints.

Within the Ontario government, the Inter-Ministerial Committee on Indoor Air Quality (henceforth called the committee) was established in 1987 to review "sick building syndrome." The Committee's mandate was to:

1. Define the terms related to indoor air quality (IAQ).
2. Review and evaluate health hazards related to IAQ.
3. Develop uniform protocol for investigating indoor air quality concerns and protocol for field measurements.
4. Recommend acceptable criteria for indoor air quality, including secondhand smoke exposure.

The committee's scope of investigation was also limited to commercial and institutional buildings. Residential and industrial buildings were excluded.

While review of the IAQ literature helped the committee to arrive at guidelines and recommendations made in this report, the protocol for investigating indoor air quality concerns, including the detailed questionnaire, was developed by the committee. *Our protocol is reactive rather than proactive.* The committee did not develop a recommendation for radon because another interministerial committee dealt with this issue.

The committee has prepared its report to guide government inspectors, occupational health professionals, and HVAC engineers in recognizing IAQ problems in nonresidential and nonindustrial buildings and in recommending remedial measures.

PROTOCOL FOR INDOOR AIR QUALITY INVESTIGATIONS

Flow Diagram

The flow diagram (Figure 1) shows the steps to be followed in the protocol for IAQ investigations. Such investigations are undertaken when complaints are received about the air in a building.

Stage 1—Preliminary Assessment

The preliminary assessment stage does not use instruments, but relies on an "inspection" and the "collection of information" on a building. The information comes from "observations" made in the building, knowledge of the operation of the HVAC system, and details of the complaints.

Two activities are involved in the preliminary assessment:

A. Collection of information about the building.
B. Interpretation of this information to provide evidence for or against the various causes of the problems.

For a complete inspection, the building checklist, given in Appendix A, should be used. Note that, whenever possible, ventilation systems should be "visually" checked to ensure that they are performing in a satisfactory manner.

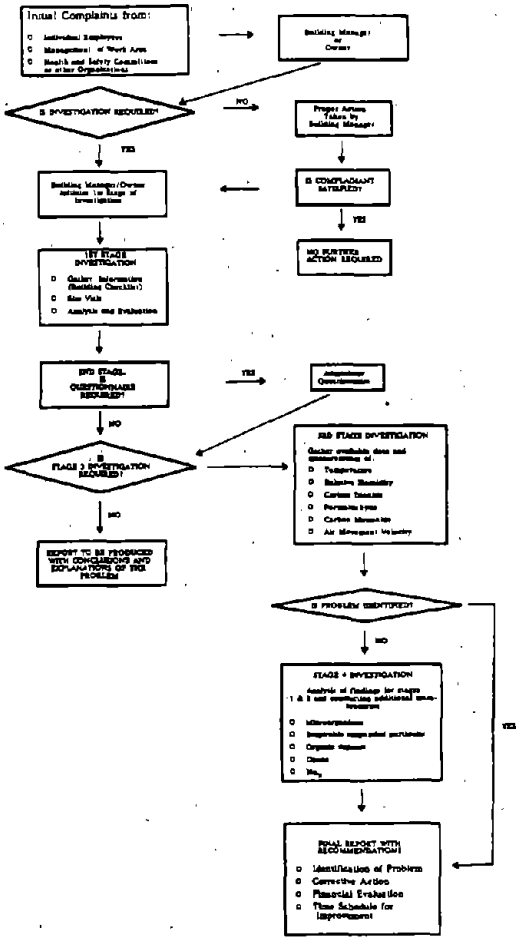

Figure 1 Protocol for IAQ investigation flow diagram

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The building checklist, divided into five parts, is as follows:

1. Carbon monoxide-combustion byproducts
2. Other pollutant sources
3. HVAC operations
4. Maintenance and design
5. Complaint area observation sheet.

Once information has been collected, the second activity in this stage is to interpret the results. Guidance on how to use the building checklist information to identify probable causes or problems is given in Part 6—Assessment Summary—of the building checklist.

The report from the preliminary assessment should include:

- Assessment of information collected.
- Recommendations for eliminating the problem.

If the cause of the problem is not identified, the questionnaire should then be administered.

Stage 2—Questionnaire and Analysis

A questionnaire has been developed as part of the protocol for IAQ investigation. The questionnaire is given in Appendix B.

The purpose of the questionnaire is to gather information on the types of problems that are experienced in the indoor environment. It has been designed to allow one to establish 1) whether and to what extent IAQ problems exist, and 2) what are the possible sources of contamination. Questions have been defined which provide an indication of exposure and the presence of the symptoms that are typically associated with each contaminant. The format and language of the questionnaire are simple so as to allow individuals to complete it without assistance.

Among the contaminants that can be assessed are: volatile organic compounds (VOC), carbon monoxide, ozone, particulates, microorganisms, and formaldehyde. Indicators of exposure to carbon dioxide, which itself is not regarded as a major contaminant, suggest the presence of ventilation problems. The questionnaire also allows assessment of the indicators of exposure and symptoms related to tobacco smoke.

The questionnaire also probes the incidence of common work environment complaints related to noise, lighting, humidity, temperature, air movement, etc.

Questionnaire Analysis

The analysis of the questionnaires for each IAQ investigation case is performed in three stages: (1) analysis of each questionnaire, (2) compilation of the results for all questionnaires, and (3) interpretation of the results.

For each contaminant, questions relating to symptoms indicate the presence of complaints typically associated with a contaminant (see Appendix C). The responses can be scored, and the higher the symptom's score, the greater the likelihood/severity that the symptoms are associated with the contaminant in question.

For each response, the presence of a symptom is scored by a value of "1." To simplify matters, it is assumed that each indicator of symptoms or exposure will have equal weighting (i.e., "1"). It is important to note that only symptoms that manifest themselves during regular working hours are of significance.

For each contaminant, exposure levels for individual responses are estimated in the same manner. High total exposure scores indicate a greater likelihood of exposure to the contaminant in question.

A series of worksheets has been developed to assist in the analysis of the questionnaire (Appendix C). A summary table for individual questionnaires will provide information about each contaminant and the severity of exposure (see Appendix D). Summary results of all questionnaires—for both symptoms and exposures—for different contaminants are compiled in a single table.

To compare scores for all individuals in an investigation, exposure and symptom scores can be plotted in the form of a frequency distribution chart (Appendix D). This chart provides information on the extent to which individual responses (relating to exposure and symptoms) vary among individuals in the survey. If high exposure and symptom scores are observed for only a small minority of individuals in the survey, the frequency distributions will reveal this.

Some indoor air problems are more severe at times in the day and/or week when the rate of fresh air distribution is lower and/or when contaminants have reached a higher concentration. A frequency distribution chart for days of the week may also assist in identifying the source of the problem.

The exposure and symptom scores can be compared for individual responses. High exposure and symptom scores may suggest that symptoms are indeed linked to the presence of a particular contaminant. If many of the responses in the survey exhibit the same pattern of high symptom scores associated with high exposure scores, then this would further suggest that there may be a widespread problem with a particular contaminant. A contingency table can be constructed and tests of significance can be performed (e.g., Chi Square) to determine whether or not there is a significant relationship between indicators of exposure and symptom intensity.

In the long term, analyses of different IAQ investigation cases may reveal trends, such as the relationship of IAQ problems to the sex of the respondents, type of office occupied, impact of other stress factors, etc.

Stage 3—Field Measurements with Simple Instruments

If the problem is not clearly identified following Stage 1 and if Stage 2 indicates a prevalence of certain symptoms or complaints, it is necessary to conduct Stage 3 of the investigation using simple instruments to take the following measurements:

- temperature
- relative humidity
- carbon dioxide
- formaldehyde
- carbon monoxide
- air movement.

It is important that the above measurements are taken in the proper location and at the appropriate time of year, week, and day. The tables in Appendix E indicate the suitable locations (including "control" locations) and time for measuring pollutants. Because the types of measurements made are unfamiliar to most people, the Data Assessment Table in Appendix F provides ranges of acceptable and unacceptable values for various pollutants. The measurement results can be compared against these ranges.

A list of simple pieces of equipment that are often used for measuring some basic pollutants is given in Appendix G. The measurements are easy to perform, and are designed to be used by non-specialists who have received a minimum of training (for example, a building operator, property manager, or safety officer).

It is expected that the data collected will prove or disprove the presence of hazardous levels of air pollutants in some cases, but not necessarily all cases. It may be necessary to go to Stage 4 to measure other potential pollutants that require complex measurement techniques.

Stage 4—Field Measurements with Complex Instruments

If the problem is not identified in Stage 3 and it is suspected that the air contamination is occurring from specific sources within or outside the building, and in the event that harmful chemicals, dust, or microorganisms are suspected, it may be necessary to do measurements of:

- microorganisms
- respirable suspended particulates
- organic vapor
- ozone
- NO_x
- asbestos.

These measurement techniques are more time-consuming and expensive to conduct than simple measurement techniques. They also require an expert to administer them. These measurements are usually only used after Stage 1, 2, and 3 evaluations have failed to resolve the situation.

Interpretation of Field Measurements

Stage 3 and 4 measurements should be compared with Appendix F of the report, which gives ranges of acceptable and unacceptable values for carbon dioxide, carbon monoxide, formaldehyde, nitrogen dioxide, ozone, and physical factors. The guideline levels for microorganisms are given in another section, "Guidelines for Indoor Air Quality," and can be used to make comparisons against measurements of microorganisms.

Several situations are possible:

- If all control and test location data fall in the normal outdoor and indoor ranges, any problems suspected are not due to this cause/pollutant.
- If control location measurements are in normal ranges and one or more test locations give numbers in the "do not exceed" range, this indicates that there are problems to be corrected.
- If control location data are in the normal range and one or more test locations give numbers in the "possible problem" range, more detailed testing may be necessary.
- If test and control locations give numbers in the "possible problem" range, the problem could lie with the outdoor air or with the equipment.

SOURCES OF CONTAMINANTS

Many contaminants have been isolated from indoor air. They can be grouped under two broad headings:

(1) those that originate from "internal" sources; and
(2) those that have their origin "outdoors."

Internal sources were classified as building components, the HVAC (heating, ventilating, and air-conditioning) system, people, furniture, office supplies and equipment, and parking garages. External sources were defined as ambient air infiltration. Common for both sources are temperature, humidity, carbon dioxide, carbon monoxide, formaldehyde, microorganisms, organic solvents, and odor. Noise, radiation, asbestos, and ergonomic and working conditions are excluded from these groups.

LIST OF OFFICES AND BUILDINGS

In developing this list (Table 1-Appendix H), only those buildings that have extended occupancy, such as places where people are present all day, are considered as opposed to intermittent occupancy, such as underground concourses. Places with intermittent occupancy were excluded because they cannot be properly evaluated using our protocol.

GUIDELINES FOR INDOOR AIR AND BUILDINGS

Factors Affecting Indoor Air Quality

The quality of indoor air in an office or public building is determined mainly by the quality of outdoor air provided, by the presence and strength of emissions from indoor sources, and by the extent of air exchange—natural or mechanically assisted—between the indoors and the outdoors. Minor influences are the reactions of chemicals and their uptake and release by surfaces.

Air pollutants generated indoors result from "human presence and activities" and fall into four main categories:

- those related to "human activity," including biological agents, products of human metabolic activity, and inorganic and organic chemicals, including personal care products used in the performance of various tasks;
- those formed by "combustion processes," including tobacco smoke;
- those given off by the "heating, ventilating, and air-conditioning equipment" and products used in their maintenance, including biological agents (bacteria, fungi, and other microorganisms and allergens); and
- those given off by the "construction materials, finishes, and furnishings" used in the building.

The concentrations of contaminants in the first three categories vary with the amount of human activity. Those in the fourth category are likely to be more constant but will decrease slowly with time, over a period of months or years, after the installation of furnishings and the construction or modification of the building.

The major causes or types of IAQ problems are: 1) inadequate ventilation (50% to 70% of cases investigated), 2) contamination from inside the building, 3) contamination from outside the building, 4) microbiological contamination, and 5) contamination from the building fabric (NIOSH 1988; Collett and Sterling 1988).

A summary of indoor pollutants, emission sources, and concentrations is shown in Table 2 (Spengler and Sexton 1983) and in Figure 2 (Nero 1988) of Appendix H. Indoor concentrations are usually higher than the outdoor concentrations because indoor sources are emitted to a confined volume of air with smaller dilution. For example, the U.S. EPA team study (Wallace 1987) found that personal air exposures for 11 volatile chlorinated and unchlorinated hydrocarbons were greater than outdoor exposures. The major reason appeared to be elevated indoor air levels at work and at home. Also, the considerable variability in the concentrations of several chemicals was caused by widely varying emission rates.

Special mention should be made of tobacco smoke. Nearly everyone is exposed at one time or another to it. This includes not only the smokers themselves, but also those who inhale the so-called sidestream smoke of others. There is increasing evidence that passive exposure to tobacco smoke may affect human health. The effects range from short-term irritation of the eyes, nose, and throat (as well as other discomfort, such as headache), to aggravation of the conditions

of people with pre-existing disease, including heart disease, lung disease, and allergies to other substances, and to cancer; chiefly of the lungs but also of other organs (Glantz 1984). The International Agency for Research on Cancer (IARC 1986) has concluded that direct inhalation of tobacco smoke is carcinogenic to both humans and animals and that passive smoking gives rise to some risk of cancer.

Tobacco smoke contributes to increased air concentrations of respirable particles, nicotine, polycyclic aromatic hydrocarbons, carbon monoxide, acrolein, nitrous oxide, and numerous other substances. Many of the components are established or suspected carcinogens, irritants, and asphyxiants. The range of concentrations found in a building is very wide and depends on the frequency and amount of smoking, air infiltration rates, air-cleaning devices, and air distribution systems (Glantz 1984).

Existing Standards and Guidelines

The symptoms and complaints associated with IAQ problems are generally nonspecific and difficult to monitor and evaluate objectively. The symptoms include eye, nose, and throat irritation; inflammation, mental fatigue, and headaches; unspecified hypersensitivity reactions and respiratory diseases such as allergic rhinitis, asthma, and hypersensitivity pneumonitis; and complaints about taste and odor. Generally, the causes are multi-factorial and it has not, in general, been possible to identify the agents and human factors responsible. Therefore, it has been difficult to develop exposure guidelines to chemical and biological agents in the nonindustrial workplace to protect workers.

Two groups have developed IAQ guidelines: the World Health Organization (WHO) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Their approaches exemplify the two possibilities for controlling indoor air quality: 1) set permissible levels for air pollutants, or 2) set minimum ventilation standards, which are intended to dilute pollutants to an acceptable level.

Existing standards and guidelines are discussed as follows under the headings of the main causes mentioned above: ventilation, indoor contamination, outdoor contamination, microbiological contamination, and contamination from the building fabric. Certain of these standards/guidelines are proposed for use in nonindustrial and nonresidential buildings.

Ventilation

ASHRAE produces ventilation standards that are used in most North American nonindustrial buildings. The standards, which are in the process of being updated, provide heating, ventilating, and air-conditioning (HVAC) engineers with two approaches for achieving acceptable ventilation levels in buildings. They are:

- ensuring that there is a prescribed minimum supply of acceptable outdoor air on a per-person and/or a per-space basis; or
- ensuring that an amount of outdoor air is supplied that will maintain indoor air pollutants below specified levels.

ASHRAE Standard 62-1981 (ASHRAE 1981) currently prescribes 5 cfm/person (2.5 L/s/person) of outdoor air for non-smoking offices. In offices where smoking is permitted, 20 cfm/person (10 L/s/person) is required. In addition, Standard 62-1981 introduced an alternative air quality procedure allowing any amount of outdoor air to be used provided that indoor air pollutants are below acceptable limits.

In 1986, a new ASHRAE standard—62-1981R (yet to be adopted)—was proposed because of new information of complaint frequencies relative to carbon dioxide levels in buildings of various occupancies and on percentage dissatisfaction with human bioeffluents, such as found in chamber studies. This standard proposes a minimum of 15 cfm/person (7.5 L/s/person) of outdoor air in any setting, with a minimum of 20 cfm/person for offices to allow for some additional air pollution such as from office equipment and a small amount of smoking. The air quality criteria to be used as alternatives to using the minimum prescribed outdoor air supply are given in Table 3-Appendix H.

The carbon dioxide limit is recommended as a surrogate measure for the lack of fresh air supply and odor levels; that is, if CO_2 is below this value, enough fresh air is supplied to dilute the pollutants (ASHRAE 1986).

The Ontario Ministry of Labour (MOL) has determined from its IAQ investigations that carbon dioxide levels can be related to the frequency of occupant complaints. The MOL's findings are given in Table 4-Appendix H, together with the equivalent air supply (Rajhans 1985). The MOL has proposed a guideline of 1000 ppm CO_2 to indicate that fresh air supply is insufficient. Carbon dioxide levels can also be used to indicate effective ventilation rates in buildings, and the calculation to do so is given in Table 5-Appendix H.

Table 1-Appendix H lists outdoor air requirements for various types of buildings. The buildings were selected by the Committee as those most likely to encounter IAQ problems. The table is also based on the occupancy classification of the Ontario Building Code.

Indoor Contamination

Offices, schools, retail spaces, and similar buildings cannot be considered as equivalent to industrial workplaces. As ASHRAE (1986) points out, the level of discomfort and irritation that is acceptable for workplaces and occupational

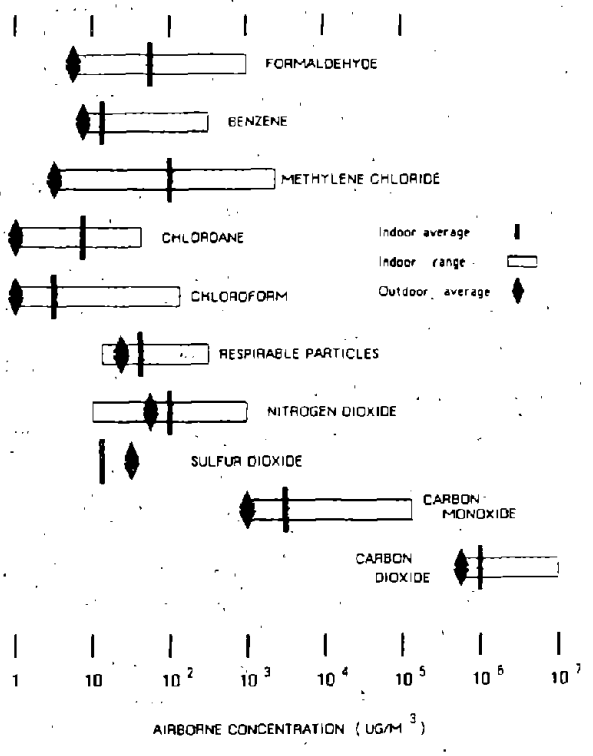

Figure 2 Indoor and outdoor air concentrations of selected pollutants (Source: Nero 1988)

exposures where chemicals are routinely used would be unacceptable for residential, office, or retail spaces. Therefore, occupational standards—for example, the threshold limit values proposed by ACGIH—are not relevant measures of IAQ in nonindustrial settings.

Canada's Federal/Provincial Advisory Committee on Environmental and Occupational Health also rejected the use of occupational limits for setting indoor air quality levels in nonindustrial buildings (HWC 1987).

ASHRAE (1986) points out that, as a preliminary guideline for nonindustrial indoor spaces, it was customary advice to assume that a concentration of 1/10 of the occupational standards would not produce complaints. However, these levels may not provide adequate protection to individuals who are very sensitive to some irritants, such as formaldehyde. The occupational standards and guidelines for some chemicals of interest in indoor air pollution are given in Table 6-Appendix H.

The World Health Organization (WHO) has also been active in this field. A Working Group of WHO has developed IAQ guidelines (WHO 1984) which are given in Table 7-Appendix H.

The guidelines developed for residential buildings by a Working Group of the Federal/Provincial Advisory Committee on Environmental and Occupational Health were released in 1987 (HWC 1987). These guidelines can be applied to nonindustrial workplaces. The reasons for applying these guidelines are that:

- all aspects of indoor air, including pollution sources and how guidelines and recommendations should be derived, were examined in the report;
- available information and guidelines from other jurisdictions were examined for their application to Canadian conditions;
- the Working Group has prepared comprehensive documentation, as yet unpublished, which gives the scientific basis for its recommendations;
- although the guidelines were not developed for other environments, such as industrial workplaces where other factors may be important (Armstrong et al. 1985), the guidelines are relevant for offices. Office environments differ little physically from residences and also contain similar construction materials, finishes, and furnishings. Both environments may also have occupants who are similarly at high risk to contaminant exposures.

The residential guidelines were developed to protect a person's health over a lifetime, "taking into account such factors as the sensitivity of groups at special risk and the sources and mechanisms of action of contaminants." Ideally one would want to develop guidelines that would protect a person at work, at home, and in the outside environment. The residential guidelines can logically include the office in addition to the home environment, and thus come close to providing this ideal.

These exposure guidelines are summarized in Table 8-Appendix H.

A comparison of the exposure ranges in Table 8 and the WHO (Table 7-Appendix H) and ASHRAE numbers (Table 3-Appendix H) is not entirely valid since the exposure times are different. Nevertheless, the concentrations in the three tables are quite close.

For substances without a specific exposure guideline, the Working Group made the following recommendations for controlling exposure:

1. Consumer products
   "It is recommended that exposures resulting from the use of consumer products be kept at a minimum by ensuring adequate ventilation and observing any other precautionary measures described on the product label and any accompanying information. Pest control products should be used only when absolutely necessary."

   In addition to pest control products, the Working Group specifically mentioned chlorinated hydrocarbons, which are used principally as solvents, cleansers, and aerosol propellants. In some cases, these may be released continuously from consumer products. The Group also mentioned that product aerosols may contain hazardous substances, both in the propellant and as the active ingredient.
2. Fibrous materials
   "Precautions should be taken to minimize inhalation of, and skin contact with, mineral fibres. Materials and products containing fibres should also be examined periodically for signs of deterioration. Advice should be sought before removing or damaging any materials thought to contain asbestos."

   The Working Group specifically mentioned asbestos and man-made mineral fibers such as fiberglass, mineral wool, and ceramic fibers. Such substances can cause transient irritation of the skin and eyes. Asbestos can cause mesothelioma, a specific form of cancer, upon prolonged exposure.
3. Lead
   "In order to minimize exposure of people . . . to lead of airborne origin, it is recommended that surfaces that may be contaminated be cleaned frequently and that a high standard of overall cleanliness be maintained."
4. Polycyclic aromatic hydrocarbons
   Exposure to these substances indoors should be kept to a minimum by ensuring that combustion systems "are properly installed and maintained and operated under conditions of satisfactory ventilation" and that the Working Group's guidelines and recommendations for particulate matter and tobacco smoke be adhered to.
5. Tobacco smoke
   "In view of the carcinogenic properties of tobacco smoke, it is recommended that any exposure to tobacco smoke in indoor environments be avoided."

Outdoor Contamination

Assuming adequate ventilation and no indoor sources of contaminants, the indoor air quality will be approximately the same as that outdoors. It cannot be assumed, however, that indoor air concentrations are necessarily the same as the ambient outdoors, since localized sources, such as garages, chimneys, and other vents may—depending on the location of the HVAC—give rise to elevated concentrations.

Table 9-Appendix H lists air quality or ambient air guidelines from some jurisdictions. These guidelines may not be relevant to shorter and higher exposures to contaminants in indoor air.

Biological Contamination

Bioaerosols include viable microorganisms (bacteria, fungi, algae, mites, viruses) and nonviable biological matter (plant pollens, animal danders, insect fragments, etc.). The microorganisms living in HVAC systems are generally saprophytic; that is, they obtain nourishment from dead organic matter and proliferate on surfaces that are wet and often dark.

Excluding infectious diseases, bioaerosols can cause allergic reactions on the skin (contact dermatitis, hyperreactivity) or in the respiratory tract (allergic rhinitis, asthma, hypersensitivity pneumonitis, pulmonary eosinophila).

The Health and Safety Support Services Branch of the MOL recommends adoption of the following guidelines as indicators of the need for improving conditions in the HVAC system:

- levels of bacteria within the HVAC system in excess of 1 x 10^5 colony-forming units (CFU)/mL in stagnant water or slime.
- levels of fungi in excess of 1 x 10^6 CFU/g in HVAC system dust.

The Federal/Provincial Working Group on Residential Air Quality (HWC 1987) has recommended the following approach for controlling biological contamination:

"In order to prevent many of the common indoor problems due to biological agents, measures should be taken to ensure that:

- excess humidity and condensation are not present,
- surfaces are kept free of dust,
- stagnant water sources such as humidifier tanks are kept clean and occasionally disinfected, and
- a high standard of appropriate personal hygiene is maintained."

Contamination from Building Materials and Products

Products such as adhesives, paints, and sealants contain solvents and other agents that can be released during and immediately after application. Organic contaminants can also be released from building materials over long time periods. One of the more notorious is formaldehyde, which emanates from chipboard, panel adhesive, carpet backing, vinyl wall covering, resin-treated fabrics, and insulation (NRC 1981).

Emissions of organics from 42 commonly used building materials have been measured and more than 50 compounds were identified. About two-thirds were aliphatic or aromatic hydrocarbons, with the remainder being ketones, alcohols, esters, aldehydes, and halogenated alkanes. Some of these compounds are suspected irritants and carcinogens. Because emission rates decrease greatly as a building ages, contamination from the building fabric is likely to be a problem mainly in new buildings (Wilfert et al. 1986).

Assuming that chemical release rates are not too high, then the ventilation and air quality guidelines outlined in this section are applicable. However, if the concentrations rise above the air quality guidelines despite the ventilation standards being met, then it may be necessary to adopt other measures, such as 1) allowing new buildings to "de-gas" until acceptable concentrations are reached, 2) using materials with low chemical release rates, 3) testing and labeling products as to their releases, or 4) isolating such products if used. However, the implementation of such measures will require considerable research as well as the setting of regulations by governments.

Recommended Guidelines for Indoor Air Quality in Non-Industrial Buildings

There are three stages to achieving acceptable air quality in offices, schools, and similar nonindustrial buildings, assuming that the make-up air is of satisfactory quality:

1. The ventilation rate per person should be higher than 7 L/s (15 cfm). This ventilation rate is equivalent to 1000 ppm CO_2

   (Tables 4 and 5-Appendix H).
2. (a) If this does not result in satisfactory air quality, then steps should be taken to meet the indoor air quality guidelines in Table 8-Appendix H. Although some jurisdictions may have lower levels, the guidelines in Table 8 have been derived after a comprehensive review of the existing knowledge about the compounds.

   (b) The qualitative guidelines in Table 10-Appendix H can also be used, although some of the health effects would only be manifested after months or years.
3. If satisfactory air quality still cannot be met, then consideration should be given to seeing whether the WHO guidelines are met (Table 7-Appendix H).

There are two objectives in the setting of standards or guidelines for indoor air quality. One objective is to control the exposure of the entire population, including susceptible groups such as those with pre-existing health conditions. Another is to avoid extreme levels, thereby limiting individual risk of disease, fatal or otherwise. The objectives can be achieved by formulating standards or guidelines that either control the factors affecting pollutant concentrations (e.g., ventilation) or by establishing concentration limits for pollutants without specifying the means by which these limits can be reached. The concentration limits for indoor pollutants as set out are probably more effective at avoiding excessive individual exposures than at controlling the average exposure of a population.

Nevertheless, the average exposure to indoor pollutants can gradually be lowered as a long-term goal. This can be achieved by establishing standards or guidelines that regulate the factors affecting indoor pollutant concentrations. For this reason, it is important to identify how source, ventilation, and structural characteristics affect indoor air quality.

The control of indoor air pollutants can be achieved through measures such as 1) prescriptions for air ventilation exchange rates and product standards for construction materials and furnishings, 2) restrictions on the use of potentially hazardous materials in products used in offices, 3) certification programs for builders and other trades, and 4) distribution of public information or a combination of all of these. Spengler and Sexton (1983) give further examples of control measures for air pollutants (Table 11-Appendix H).

The guidelines for indoor air quality presented in this paper can provide a reference point for assessing the extent to which such remedial measures need to be taken. The precise manner in applying and implementing these guidelines will have to be determined through further discussions with those groups whose activities and responsibilities encompass these areas (Wylie and Armstrong 1986).

The Committee did not find any IAQ standards established for children in schools. It has been reported that factors related to younger age groups include a higher respiration rate per unit body weight and less ability to comprehend and communicate adverse health effects. Another factor to be considered is aggravation of pre-existing disease in children. The guidelines proposed here appear to be stringent enough to protect the health of adult office workers as well as school children, hence the recommendation for its adoption.

SECONDHAND SMOKE EXPOSURE

Cigarette smoke is a complex mixture of several hundred substances: irritants (aldehydes), toxic chemicals (carbon

monoxide), and carcinogens (benzo (a) pyrenes, tars, etc.). More than 50 of these are known to cause adverse health effects: 12 are known or suspected carcinogens.

In the office environment, the primary complaint is one of irritation to the eyes and upper respiratory tract, usually caused by the aldehydes present. Unfortunately, it is difficult to ascertain an individual's exposure to irritants by means of an ambient air measurement alone. Irritating aldehydes disperse in the room air so that their total concentration is low—much lower than reported irritant levels. However, measurements taken directly in the breathing zone of the exposed person can show levels several hundred times the irritant concentration (Ayer 1983).

Of more concern, however, are the findings of studies that suggest an increased risk of lung cancer in non-smokers exposed to cigarette smoke (Hirayama 1981). In addition, certain epidemiological studies have pointed to an increase in respiratory illness in children exposed to secondhand cigarette smoke (House 1985). Other health effects in non-smokers include headache, nausea, dizziness, loss of appetite, aggravation of asthma, or angina.

It has been estimated that 63% of non-smokers are exposed to tobacco smoke at work and 86% of non-smokers either at home, at work, or both. The ambient concentrations of secondhand smoke are much lower than the concentration to which active smokers are exposed. Thus, it has been calculated that, in an office where many people smoke, secondhand exposure is equivalent to one to five cigarettes per day (House 1985). Statistical analyses have been conducted to predict that approximately 5000 persons in the U.S. die annually from lung cancer caused by exposure to secondhand cigarette smoke (Repace 1982).

To date, no one satisfactory method is available to measure the amount of cigarette smoke present in a workplace. Concentrations of carbon monoxide are sometimes used as an indicator of irritation complaints. Other more specific pollutants (such as nicotine and formaldehyde) are present in such low concentrations in ambient air that they cannot be used as practical indicators. Other components present in larger concentrations have many sources besides cigarette smoke, e.g., carbon dioxide is a human metabolite and particulates can arise from paper, furnishings, clothing, etc.

Building inhabitants should be encouraged to adopt a non-smoking policy, both in view of the health implications for non-smokers and the fact that smoking is the largest preventable cause of death in Canada. This has been done for many Ontario Ministries and municipal by-laws have been enacted to this effect, e.g., Toronto (Hauser 1984). Designated non-smoking areas, without a separate ventilation system, are not effective in restricting exposure to secondhand smoke. Separate ventilation systems for smoking areas have been recommended, but retrofitting an existing workplace with separate ventilation systems is often economically impractical (Hauser 1984).

CONCLUSIONS

Adoption of uniform definitions of indoor air quality (IAQ) terminologies and a uniform protocol of IAQ investigations is recommended. Details are given in the report (Province of Ontario 1988). Part of the recommended protocol is a comprehensive questionnaire and its analysis.

Because the sources of indoor pollutants cannot be avoided in most cases, the Committee proposes that adequate fresh air supply is the single most effective solution to IAQ problems, provided that heating, ventilating, and air-conditioning (HVAC) systems are properly designed, operated, and maintained. For buildings without a complete mechanical ventilation system, full advantage should be taken of the ventilation provided by openable windows.

The guidelines presented in this paper for IAQ provide reference points for assessing the extent of remedial measure in buildings.

The Committee was unable to find any regulatory standards for IAQ specifically established for children in schools. However, the guidelines proposed in this paper are stringent enough to protect the health of school children. The guidelines in Table 8-Appendix H were developed by taking into account high-risk groups such as the very young and elderly.

The Committee recommends adoption of a non-smoking policy by Ontario Ministries due to the presence of several known or probable carcinogens as well as other toxins in "mainstream" and "sidestream" smoke. Until such time as the non-smoking policy is adopted, buildings should be provided with designated smoking areas with a separate exhaust and ventilation system.

The Committee recommends that appropriate changes be made to the Ontario Building Code to reflect the findings of this report.

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APPENDIX A

BUILDING CHECKLIST
(SOURCE: Public Works Canada. Indoor Air Quality Test Kit: User Manual, 1988.)

PART 1: CARBON MONOXIDE — COMBUSTION BY-PRODUCTS

Possible sources of carbon monoxide and combustion by-products in the building are identified below. Go down the numbered list of sources. Indicate whether or not this building does contain each (choose YES / NO by underscoring, circling etc.). If the answer is "NO," go to the next numbered question. If the answer is "YES," answer the rest of the questions in the paragraph (which all concern this source) before going to the next numbered question.

1)	Does the building contain an *internal parking garage?*	YES / NO
	Is the garage enclosed with a ventilation system?	Yes / No
	If so, is the ventilation system controlled by carbon monoxide sensors?	Yes / No
	Is it more than six months since the carbon monoxide sensors were recalibrated?	Yes / No
	Are there any obstructions in the exhaust or fresh air?	Yes / No
	Is the garage full for most of the day?	Yes / No
	Are there cars coming and going for most of the day?	Yes / No
	Does the checkout booth lack its own ventilation?	Yes / No
2)	Does the building contain an *internal loading dock?*	YES / NO
	Is there an outer door which is closed after a truck's arrival?	Yes / No
	Do the drivers keep their motors running in the dock?	Yes / No
	Are there usually more than ten deliveries each day?	Yes / No
	Are doors to other parts of the building kept open?	Yes / No
	Is the reception office open to the loading dock?	Yes / No
	Does the reception office lack its own ventilation?	Yes / No
3)	Does the building contain *a kitchen with gas stove(s)?*	YES / NO
	Are the exhaust hoods above the stoves missing or faulty?	Yes / No
	Are the stoves often operated without the exhausts switched on?	Yes / No
4)	Does the building contain a *gas-fired heating system?*	YES / NO
	Are there any signs of leaks in the furnace or chimney?	Yes / No
	Is the chimney vented into the building ventilation system rather than direct to outdoors?	Yes / No
5)	Does the building contain any *small free-standing gas heaters?*	YES / NO
	Is there a smell of gas or burning around the heaters?	Yes / No
	Is the exhaust vented into the building ventilation system rather than direct to outdoors?	Yes / No

PART 2: OTHER POLLUTANT SOURCE

Possible sources of volatile organic compounds (VOC), formaldehyde, and biological material in the building are covered in this part of the checklist. As before, indicate whether or not this building does contain each potential source by answering the numbered questions. If the answer is "NO," go to the next numbered question directly. If the answer is "YES," answer the rest of the questions in the paragraph before moving on.

6)	Are there *shower facilities* in the building?	YES / NO
	Are these facilities used more than ten hours a week?	Yes / No
	Is there any mold visible on the floor or walls of the shower stalls, the shower heads or shower curtains?	Yes / No
	Are there moldy odours in the shower stalls or nearby?	Yes / No
7)	Does the building contain *wet-process photocopiers?*	YES / NO
	Are any of these machines in small rooms with no air supply or exhaust?	Yes / No
	If *yes* give the locations of these machines.	
	_____ _____ _____	
8)	Does the building contain a *printshop?*	YES / NO
	Are solvents regularly used to clean the equipment?	Yes / No
	Are the waste rags or paper used during cleaning disposed of in an open garbage can?	Yes / No
	Are any of the bottles or cans of chemicals	Yes / No

usually left open or with the lids loose?
Do any of the machines lack an exhaust hood? Yes / No

9) Does the building contain a *laboratory which uses chemicals (for cleaning, processing, conservation, etc.)?* YES / NO
Are volatile chemicals used frequently? Yes / No
Are these volatile chemicals used without the protection of fume hoods? Yes / No
Is there a persistent odour in the laboratory area? Yes / No
Does the laboratory use the same ventilation system as the rest of that area of the building? Yes / No

10) Does the building contain *stored chemicals* (pesticides, waste solvents, etc.)? YES / NO
Do any of the chemicals stored evaporate quickly? Yes / No
Are any of the bottles or cans left open or with the lids loose? Yes / No
Is there a persistent odour in the storage area? Yes / No
Is the storage area unventilated? Yes / No

11) Does the building contain a storeroom or storage area with *shelves made of plywood or particleboard?* YES / NO
Is the plywood or particleboard used as bought, without a coat of paint or varnish? Yes / No
Is the storage area unventilated? Yes / No
Is there a persistent odour in the storage area? Yes / No

12) Is there a ban on smoking in this building? YES / NO
Is the ban only partial, with special smoking rooms allowed? Yes / No
If *Yes*, give locations of these rooms:

_____ _____ _____

Do any of these lack both a window fan and an electrical air cleaner?

Yes / No Yes / No Yes / No

Do any of these have a fan or window fan that blows the smoky air out through the door?

Yes / No Yes / No Yes / No

13) Are large amounts of *paper* stored in the building? YES / NO
If *YES*, give the location:

_____

Does frequent movement of paper take place? Yes / No
Is there dust on surfaces in this area? Yes / No

PART 3: HVAC OPERATION

As before, if the answer to a numbered question is "YES," answer the rest of the questions in that paragraph (if any). Otherwise, go to the next numbered question.

If the building contains two or more towers or wings which are essentially separate, and are controlled by different HVAC systems, a copy of this sheet should be filled out for each.

14) Is the *amount of fresh air* used by the ventilation system the same all year round? YES / NO
What is the percentage fresh air used? _____

15) Is the building run on an *economizer cycle?* YES / NO
What is the maximum percentage of fresh air used? _____
What is the minimum percentage of fresh air used? _____
What is the fresh air percentage just now? _____

16) Is *air* supplied to the floors by:
constant volume boxes / VAV boxes / heat pumps?

17) At what temperature is the tank supplying *hot water* to the building maintained? _____

18) Does the building contain *fresh air intakes?* YES / NO
Are the intakes below third floor level *and* above a busy street? Yes / No
Are the intakes above the entrance to a loading dock? Yes / No
Are the intakes above the entrance or exit to a parking garage? Yes / No
Are there any other pollution sources near the intakes? Yes / No
If *Yes*, describe them:

_____

Are there obstructions (i.e. birds' nests) lodged in the air intake? Yes / No
Are the intakes within 10 meters (30 feet) of the exhausts of this or an adjacent building? Yes / No

19) Is the *ventilation in the work areas* decreased or shut off overnight or at weekends? Yes / No
If *decreased*, the system goes down overnight to _____% of daytime.
Shut-off/decrease hours are from _____pm to _____am

20) Does this building have *a particulate (dust) filter* system installed in the fresh air intake? YES / NO
Are the filters changed less frequently than recommended by the manufacturer? Yes / No
Does the filter fit so poorly that air bypasses it at the edges? Yes / No
Are the filters matted or dirty? Yes / No

21) Are *spray humidifiers* used in this building? YES / NO
Are they operating today? Yes / No
Are the pans drained less often than once a week? Yes / No
Is there slime in the humidifier pans? Yes / No
Are there moldy odours? Yes / No
Is there mold on the ducts on the building side of the humidifiers? Yes / No
Is the water hard in this region? Yes / No
If so, are there hard water deposits on the vanes? Yes / No
Are the hard water deposits removed by scraping the vanes and blowing the dust into the ducts? Yes / No

22) Are *steam humidifiers* used in this building? YES / NO
Are they operating today? Yes / No
Are volatile chemicals used in the boiler or the pipes to prevent corrosion? Yes / No
If *Yes*, names of chemicals are:

_____

23) Does this building have an *air-conditioning system?* YES / NO
Is the system operating today? Yes / No
Are the condensate trays cleaned less often than once a week? Yes / No

Is there slime on the condensate trays? Yes / No
Is there slime on the cooling coils? Yes / No
Are there moldy odours in the system? Yes / No

24) Are the ventilation ducts or plenums *insulated?* YES / NO
Is the insulation on the inside? Yes / No
Is it more than five years since the ducts or plenums were last cleaned? Yes / No

PART 4: MAINTENANCE AND DESIGN

As before, if the answer to a numbered question is "YES," answer the rest of the questions in that paragraph (if any). Otherwise go to the next numbered question.

25) What year was the building constructed? _____
Was the building commissioned after occupancy? Yes / No

26) Can the *windows in the work areas be opened?* YES / NO
Do the occupants frequently open the windows? Yes / No

27) Have any *open office spaces been converted to closed offices* since the building was opened? YES / NO
If *YES*, give location:

Was the original ventilation retained in this area? Yes / No
Do most of the closed offices lack thermostats? Yes / No

28) Have structural alterations resulted in *increased occupant density* anywhere in the building? YES / NO
(i.e. conversion of office space to boardrooms or waiting rooms)
If *YES*, give location:

Was the original ventilation retained in this area? Yes / No
Does this space lack a thermostat? Yes / No
Is this space used for more than two hours each day, or ten hours a week? Yes / No
What is the peak occupant density?
_____ people in _____ sq. feet

29) Are any work areas being *recarpeted* just now? Yes / No
If *YES*, give the location:

Do odours persist for more than a week after the carpet has been laid? Yes / No

30) Are any work areas being *repainted* just now? YES / NO
If *YES*, give the location:

Do odours persist for more than a week after the paint has been applied? Yes / No

31) Is there *foam insulation* in the walls of the building? YES / NO
Is it Urea Formaldehyde Foam Insulation? Yes / No / do not know

PART 5:
COMPLAINT AREA OBSERVATION SHEET

no._____

Floor: _____ Room/Workstation:_____

All the questions should be answered. Where a choice of answers is given, please circle or underscore the most appropriate.

1) *General Observations* Yes / No
Are there damp patches or mold on the wall or ceiling?
Are there a lot of potted plants in this area? Yes / No
Is there mold on the plants or their pots or soil? Yes / No
Are there odours here? Yes / No
If *Yes*, describe the odours:

Are people using fans to make more air movement? Yes / No
Is there a lot of dust visible on flat surfaces? Yes / No

2) Is this room an *enclosed office* (with walls and door)? Yes / No
If *Yes*, is it missing a thermostat? Yes / No

3) Is this an *open office* area? Yes / No
If *No*, go to question 4.
Are screens used to divide the area up? Yes / No
If *No*, go to question 4.
Are the screens more than five feet high? Yes / No
What is the average area enclosed by the screens? _____sq. ft.

4) Check the *air supply diffusers.*
Does this room lack supply air? Yes / No
Can you see any of the following on or around the diffusers?
mold / chalky dust / dirt marks
Are any of the diffusers blocked by furniture, papers or any other obstruction? Yes / No

5) Check the *air exhaust louvers.*
Does this room lack exhaust? Yes / No
Are there dirt marks on or around the louvres? Yes / No
Are any of the louvers blocked by furniture, papers or any other obstruction? Yes / No

6) Are any of the following *pollutant sources* within 30 feet (10 metres) of this room/workstation:
wet-process photocopier? Yes / No
printshop? Yes / No
room where chemicals are used? Yes / No
room where chemicals are stored? Yes / No
area with plywood/particleboard shelves? Yes / No
smoking room? Yes / No
an area with a lot of stored paper? Yes / No

Comments:

PART 6: ASSESSMENT SUMMARY

Three things are needed before an air quality problem needs further investigation using simple instruments. You can remember them as *PIP*, *P*eople, *I*nadequate ventilation and *P*ollutants. The presence of people is important, and problems can sometimes be tolerated in unoccupied areas such as basement mechanical rooms. Ventilation which is adequate in one situation, such as a large office, may be inadequate in

another, such as a printshop. It all depends on the balance between the capacity of the ventilation system and the strength of the pollutant sources.

An assessment procedure is described below for each of the parts of the Checklist questionnaire. Most of the questions have been worded so that a "Yes" answer means a possible problem. The simplest assessment procedure just consists of counting the number of "Yes" answers. Sometimes it is necessary to refer to the answers of other questions to obtain an effective assessment.

Part 1: Carbon monoxide/combustion byproducts

The numbered questions each refer to a possible source of carbon monoxide/combustion products in the building. For each of these that the building contains (a "Yes" answer), problems are *only* likely if one or more "Yes" answers are obtained to the other questions in the same paragraph. The more "Yes" answers, the more chance of a problem.

Part 2: Other Pollutants

The numbered questions each refer to a possible pollutant source in the building. For each of these that the building contains (a "Yes" answer), problems are *only* likely in practice if "Yes" answers are obtained for other questions in the same paragraph. The more "Yes" answers, the more chance that this pollutant source will be causing problems. The pollutant sources that the numbered questions refer to are:

6) fungi if mold visible anywhere, or moldy odours present
7) volatile organic compounds (VOC)
8) VOC
9) VOC
10) VOC
11) formaldehyde
12) biological material such as fungi and bacteria
17) particulates

Part 3: HVAC Operation

Some of the numbered questions are followed in the same paragraph by other questions requiring a Yes/No answer. A "Yes" answer to the numbered questions *only* indicates that a problem is likely if one or more "Yes" answers are obtained to the other questions in the same paragraph. The more "Yes" answers, the more chance of a problem.

The types of problems indicated by the answers are indicated below:

14) and 15) Less than 10% fresh air is likely to result in non-compliance with ASHRAE standards.
16) VAV boxes respond to temperature, and may not be effective in dealing with strong local pollution sources.
17) If the temperature is higher than 55° C, legionella bacteria cannot survive.
18) — Carbon monoxide may be a problem if the intakes are either just above a busy street, or close to a loading dock or parking garage that have been identified as potential problem sources (check answers to questions (1) and (2));
— particulates may be a problem if there are obstructions in the intake *and* particulate filters either are not used in the HVAC system, or are poorly maintained (check question (20));
— contaminated air from the exhausts can re-enter the building if intakes and exhausts are too close. This will increase concentrations of all pollutants.
20) particulates, see question (18).
21) — biological contamination can be caused by spray humidifiers if the pans are not kept clean;
— particulate problems can be caused by spray humidifiers but *only* if the local water is hard *and* the cleaning procedure allows hard water solids to enter the ventilation ducts.
22) VOCs used to protect the boiler or steam pipes may enter the ventilation system and be distributed around the building.
23) Biological contamination can result if the air-conditioning system is not cleaned regularly. Most outbreaks of legionellosis are caused in this way, and fungal contamination is also possible.
24) Particulates originating in the ducts or plenums; these can be accumulated dirt, or insulation fibers (if the insulation is on the inside of the duct or plenum). If the insulation looks like it is a problem, check to see whether it is asbestos. Building Performance can supply information on PWC's asbestos program.

Part 4: Maintenance and Design

Some of the numbered questions are followed in the same paragraph by other questions requiring a Yes/No answer. A "Yes" answer to the numbered questions *only* indicates that a problem is likely if one or more "Yes" answers are obtained to the other questions in the same paragraph. The more "Yes" answers, the more chance of a problem.

The types of problems indicated by "Yes" answers are indicated below:

26) inadequate ventilation (fresh air or air circulation)
27) temperature/carbon dioxide
28) carbon dioxide
29) VOC
30) VOC
31) formaldehyde. If the answer here is "do not know," check the building plans, which should contain this information. If this is unsuccessful, extract a small piece of the insulation from the wall cavity, and send it to Building Performance for testing.

Part 5 — COMPLAINT AREA OBSERVATION SHEET

To do the assessment, place this sheet to the right of the completed COMPLAINT AREA OBSERVATION SHEET, and overlap it, so that the numbered paragraph headings line up (a ruler is useful). The assessment for each answer can then be read off directly.

1) *General Observations*
Yes = biological
Yes = possible biological (mold). Check answer to next question
Yes = increases the probability of biological problem
Yes = almost any pollutant. To try to determine which one, check descriptions against the table of odours on the next page and enter the most likely:

Yes = carbon dioxide (ventilation)
Yes = particulates

2) *Enclosed Office* = Yes
Yes (*no* thermostat) = temperature / carbon dioxide (ventilation)

3) *Open Office* = Yes
Yes = carbon dioxide (local air circulation)
Yes increases probability of carbon dioxide (local air circulation)
Yes increases probability of carbon dioxide (local air circulation average area less than 100 sq. ft. increases the probability

4) *Air Supply Diffusers*
Yes = carbon dioxide (ventilation)
mold = biological; *chalky dust* = particulates from struc-

tural alterations *or* spray humidifier: *dirt marks* = particulates in the ventilation system
Yes = carbon dioxide

5) *Air Exhaust Louvers*
Yes = carbon dioxide (ventilation)
Yes = particulates in the room or nearby
Yes = carbon dioxide

6) *Pollutant Sources* within 30 feet (10 meters)
Yes – check question 7 for likely source strength (VOC)
Yes – check question 8 for likely source strength (VOC)
Yes – check question 9 for likely source strength (VOC)
Yes – check question 10 for likely source strength (VOC)
Yes – check question 11 for likely source strength (formaldehyde)
Yes – check question 12 for likely source strength (particulates)
Yes – check question 13 for likely source strength (particulates)

APPENDIX B

INDOOR AIR QUALITY SURVEY

This questionnaire is designed to help assess the quality of the indoor environment at _____.

Your answers will remain confidential and they will be used for analyses only.

The questionnaire is collecting data on your working environment, health and lifestyle. Questions are answered by checking the appropriate box ☑, circling the appropriate answer (glare), or by filling in a blank _____. There is also space for additional comments.

We are grateful for your help in completing this questionnaire. Please check that you have answered all the questions before sealing the questionnaire in the confidential return envelope.

Hand the sealed envelope to _____ who will be in the office while you are completing the questionnaire.

Date: _____ Time: _____

DESCRIPTION OF JOB AND OFFICE

(1) What is your employment status?

Full time ..... ☐
Part time ..... ☐
Temporary ..... ☐
Other (Specify) _____

(2) I have worked in this area since (year) _____, (month) _____, (day) _____.

(3) How many hours per week do you work in this area? _____ hours.

(4) I am in:

a closed office ☐
my own cubicle ☐
an open area shared with others ☐
Other _____
(Specify)

(5) What is the location of your desk? (Identify on floor map if attached.)

(6) Are you sitting within 3.7 meters (12 feet) of a window?

Yes ☐ No ☐

(7) Can the window be opened?

Yes ☐ No ☐

(8) Within 10 metres (approximately 33 feet) of your work location is there:

(a) typewriter. . . . . Yes ☐ No ☐
(b) a photocopying machine? . . . . . Yes ☐ No ☐
(c) a keyboard with a video display screen
(e.g. VDT, CRT, data or word processor)? . . . Yes ☐ No ☐
(d) a printer . . . . . Yes ☐ No ☐
(e) a teletype or fax machine? . . . . . Yes ☐ No ☐
(f) posting-machine? . . . . . Yes ☐ No ☐
(f) other (specify)? _____

(9) For each equipment that you work with, list the number of hours that you use the machine on a typical day.

Equipment	Hours per day

DURING THE PREVIOUS WEEK WHILE WORKING IN YOUR AREA:			
Check "Yes" if symptoms interferred with work.	Circle the symptoms which have given you trouble.	How long did the symptoms last?	Circle when the symptoms are worst?
(10) Nasal symptoms Yes ☐ → No ☐ ↓	nosebleeds, congestion, sinus problems, sneezing, runny nose, dry nose, other: _____ (specify)	_____ (hours)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm
(11) Throat Symptoms Yes ☐ → No ☐ ↓	sore throat, dry cough, other: _____ (specify)	_____ (hours)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm
(12) Eye symptoms Yes ☐ → No ☐ ↓	redness, watering, burning, puffiness, dryness, irritation, blurred vision, other: _____ (specify)	_____ (hours)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm

DURING THE PREVIOUS WEEK WHILE WORKING IN YOUR AREA:			
Check "Yes" if symptoms interferred with work.	Circle the symptoms which have given you trouble.	How long did the symptoms last?	Circle when the symptoms are worst?
	CONTACT LENS WEARERS ONLY		
(13) Problems related to wearing contact lenses Yes ☐ → No ☐ ↓	problems with: cleaning, deposits, discomfort, pain, other: _____ (specify)	_____ (hours)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm
(14) Skin Problems Yes ☐ → No ☐ ↓	Dryness, flaking, rash, irritation, other: _____ (specify)	_____ (hours)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm
(15) Aches and Pains Yes ☐ → No ☐ ↓	headache, backache, muscle/joint pain, other:_____ (specify)	_____ (hours)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm
(16) General Complaints Yes ☐ → No ☐ ↓	drowsiness, dizziness, faintness, difficulty in concentration, other: _____ (specify)	_____ (hours)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm

DURING THE PREVIOUS WEEK WHILE WORKING IN YOUR AREA:

Check "Yes" if symptoms interferred with work.	Circle the symptoms which have given you trouble.	How long did the symptoms last?	Circle when the symptoms are worst?
(17) Other symptoms Yes ☐ → No ☐ ↓	breathing, digestive, menstrual, other: _____ (specify)	_____ (hours)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm

(18) Were you ever absent because of any health problem(s) that you feel may have been caused or aggravated by working at your present location?

Yes ☐ → If yes, state the health problem: _____

No ☐ ↓

(19) Did you seek medical treatment because of any health problem(s) caused or aggravated by working at your present location?

Yes ☐ No ☐

WORKING ENVIRONMENT: Please record your general assessment of the working environment at your present location.

Check "Yes" if disturbing	Circle the aspects which are disturbing	Circle when the problems are most disturbing?
(20) Noise Yes ☐ → No ☐ ↓	Noise from: • nearby conversation • lighting • ventilation system • office equipment • other _____ (specify)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm
(21) Ventilation Yes ☐ → No ☐ ↓	• temperature • humidity • air movement • other _____ (specify)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm
(22) Lighting Yes ☐ → No ☐ ↓	• too bright • not bright enough • glare, flicker • other _____ (specify)	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm
(23) Others Yes ☐ → No ☐ ↓	Specify: _____ _____ _____	Mon: am pm Tues: am pm Wed: am pm Thurs: am pm Fri: am pm

(24) If there is a smell in your area, how would you describe the smell?

(a) The smell resembles:

- Glue ☐
- vinegar ☐
- alcohol ☐
- ammonia ☐
- propane ☐
- gasoline ☐
- perfume ☐
- other _____ (specify)

(b) It smells:

- smoky ☐
- dusty ☐
- musty ☐
- stale ☐
- other _____ (specify)

(25) In your opinion, where is the smell coming from?

_____

_____

(26) Do you use any of the following in your work location?

Check appropriate box:

- (a) a desk lamp ☐
- (b) a fan ☐
- (c) a heater ☐
- (d) humidifier ☐
- (e) an ion generator ☐
- (f) an air cleaner ☐
- (g) personal care products (e.g. hand cream, hairspray) ☐
  (Please specify what products) _____ ☐
- (h) No items

(27) Have you any control over your work location? Check appropriate box:

(a) ventilation ☐
(b) temperature ☐
(c) humidity ☐
(d) lighting ☐

(28) Is smoking allowed in or near your working location?

No ☐ → If No go to question 32.
Yes ☐

(29) How many cigarettes a day do you smoke at your work location?

None ☐
Less than 10 ☐
Between 10 and 30 ☐
More than 30 ☐

(30) Do you smoke any other tobacco product at your work location (e.g. pipe, cigar)?

Yes ☐ → Amount smoked per day:
No ☐ Cigars _____
Ounces of tobacco _____

(31) Do other people smoke in your area?

Yes ☐ No ☐

(32) Is there a designated smoking area?

Yes ☐ No ☐

(33) Do you have allergies?

Yes ☐ No ☐

→ Yes you are allergic to: _____

(34) Are you taking any prescribed medication for any symptoms you mentioned?

Yes ☐ No ☐

GENERAL INFORMATION

(35) Age (in years) _____

(36) Sex: Male

Female

ARE THERE ANY FURTHER COMMENTS WHICH YOU WOULD LIKE TO MAKE?

_____

_____

_____

THANK YOU FOR FILLING IN THIS QUESTIONNAIRE

APPENDIX C

A) Analysis of Individual Responses

For answers relating to symptoms only those symptoms which occur during working hours will be considered.

Contaminant - 1
VOC

1. Symptoms - Incidence and Severity

Q.10 Score	Q.12 Score	Q.13 Score	Q.14 Score
10.1.3	12.1.1	13.1.1	14.1.1
10.1.4	12.1.2	13.1.2	14.1.2
10.1.5	12.1.3	13.1.3	14.1.3
	12.1.4	13.1.4	14.1.4
	12.1.5		
	12.1.6		
Sum	Sum	Sum	Sum

Total Score _____

2. Exposure

Q.8 Score	Q.9 Score	Q.24 Score	Q.26 Score
8.1	9.1	24.1.1	26.7
8.3	9.3	24.1.2	
8.4	9.4	24.1.3	
8.5	9.5	24.1.4	
Sum	Sum	Sum	Sum

Total Exposure Score _____

Contaminant - 2
Formaldehyde

1. Symptoms

Q.11 Score
11.1.1
11.1.2
11.1.3

Sum =

Total Score _____

2. Exposure

Q.24 Score
24.1.5
24.1.6
24.2.1

Sum =

Total Exposure Score _____

Contaminant - 3
Ozone

1. Symptoms

Q.10 Score	Q.11 Score
10.5	11.1
	11.2
	11.3
	11.4
	11.5
Sum=	Sum=

Total Score _____

2. Exposure

Q.8 Score	Q.9 Score
8.1	9.1
Sum=	Sum=

Total Exposure Score _____

Contaminant - 4
Carbon Monoxide - CO

1. Symptoms

2. Exposure

Q.24 Score	Q.29 Score	Q.30 Score	Q.31 Score
24.1.5	29.2	30	31
24.1.6	29.3		
24.2.1	29.4		
Sum=	Sum=	Sum=	Sum=

Total Exposure Score _____

Other Factors-5
Relative Humidity

1. Symptoms

Q.10 Score	Q.11 Score	Q.16 Score
10.1.1	11.1.7	16.1.1
10.1.2		16.1.2
10.1.3		16.1.3
		16.1.4
Sum =	Sum =	Sum =

Total Score _____

2. Exposure

Q.24 Score	Q.26 Score	Q.27 Score
24.2.3	26.4	27.3
Sum =	Sum =	Sum =

Total Exposure Score _____

Other Factors - 6
Carbon Dioxide - CO_2

1. Symptoms

N/A

2. Exposure

Q.24 Score
24.2.1
24.2.4

Sum =

Total Exposure Score _____

Other Factors - 7
Temperature

1. Symptoms

   N/A

2. Exposure

Q.21	Score	Q.26	Score
21.1		26.2	
		26.3	
Sum =		Sum =	

Total Exposure Score _____

Other Factors - 8
Air Movement

1. Symptoms

Q.21	Score
21.1.3	
Sum =	

Total Score _____

2. Exposure

Q.26	Score
26.2	
Sum =	

Total Exposure Score _____

CONTAMINANT - 10
BIOLOGICAL SUBSTANCES

1. Symptoms

Q.18	Score	Q.19	Score
18.1		19.1	
Sum=		Sum=	

Total Symptoms Score =

2. Exposure

Q.21	Score	Q.26	Score
21.2		26.4	
Sum=		Sum=	

Total Exposure Score =

CONTAMINANT - 11
PARTICULATES

1. Symptoms

   N/A

2. Exposure

Q.24	Score	Q.29	Score	Q.30	Score	Q.31	Score
24.2.1		29.2		30.1		31.1	
24.2.2		29.3					
24.2.4		29.4					
Sum=		Sum=		Sum=		Sum=	

Total Exposure Score =

Stress Factors - 9
Noise, Lighting, etc.

1. Symptoms

Q.12	Score	Q.16	Score
12.1		16.1.1	
12.2		16.1.2	
12.3		16.1.3	
12.4		16.1.4	
12.5		16.1.5	
12.6			
Sum =		Sum =	

Total Score _____

2. Exposure

Q.7	Score	Q.20	Score	Q.22	Score
7.2		20.1		22.1.1	
		20.2		22.1.2	
		20.3		22.1.3	
Sum =		Sum =		Sum =	

Total Exposure Score _____

CONTAMINANT - 12
SECOND HAND SMOKE

1. Symptoms

Q.10	Score	Q.12	Score	Q.15	Score	Q.16	Score
10.3		12.1		15.1.1		16.1.1	
10.4		12.2					
10.6		12.3				Q.17	
		12.6					
						17.1.1	
Sum=		Sum=		Sum=		Sum=	

Total Symptoms Score =

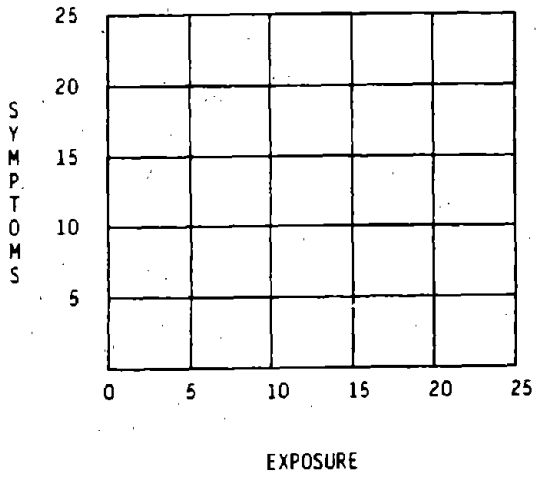
2. Exposure

Q.31	Score
31.1	
Sum=	

Total Exposure Score =

APPENDIX D

CONTINGENCY TABLE



APPENDIX D

TOTAL SCORE TABLE

QUESTIONNAIRE NO	SYMPTOMS												EXPOSURE											
	1 VOC	2 FOR	3 OZO	4 CO	5 RH	6 CO_2	7 T	8 AIR	9 STR.	10 BIO	11 PAR	12 SMO	1 VOC	2 FOR	3 OZO	4 CO	5 RH	6 CO2	7 T	8 AIR	9 STR.	10 BIO	11 PAR	12 SMO
1																								
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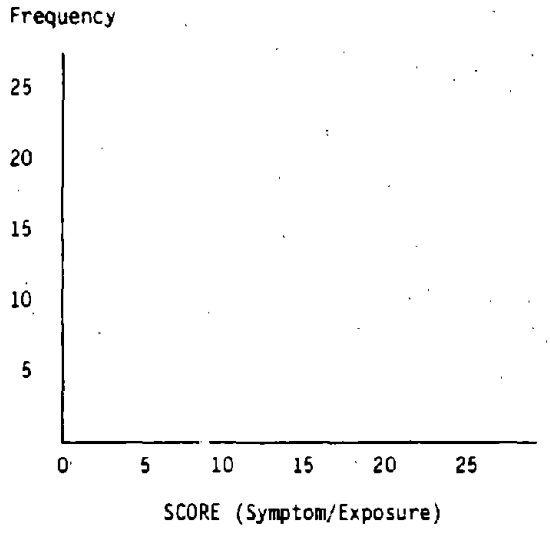
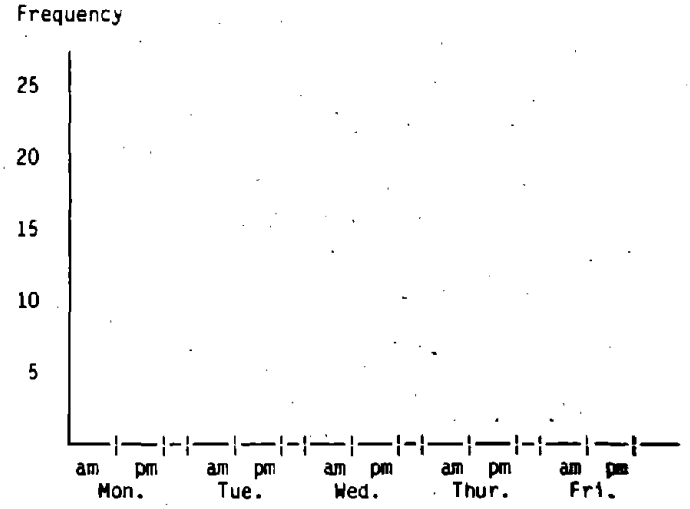
FREQUENCY DISTRIBUTION FOR EACH CONTAMINANT SYMPTOMS/EXPOSURE



FREQUENCY DISTRIBUTION FOR DAYS OF THE WEEK



APPENDIX E

WHERE AND WHEN TO MEASURE
(SOURCE: Public Works Canada. Indoor Air Quality Test Kit: User Manual, 1988.)

TABLE 1

Test Locations for Measuring Pollutants and Other Parameters Related to Indoor Air Quality

Pollutant or Parameter	Test locations	Time to measure
carbon dioxide	pollutant sources (questions 31, 32) complaint areas	late morning, late afternoon, when fresh air rate low
carbon monoxide combustion	pollutant sources (questions 1–5, 22) complaint areas near sources	early morning, late afternoon, when fresh air rate low
formaldehyde	pollutant sources (building) (questions 15, 35) complaint areas near sources	early morning, when fresh air rate low
particulates	pollutant sources (questions 16, 17, 24, 28) complaint areas near sources	
VOC	pollutant sources (building) (questions 14, 26) complaint areas near sources	early morning, Mondays, when fresh air rate low
VOC	pollutant sources (activity) (questions 12, 13, 33, 34) complaint areas near sources	late morning, late afternoon, when fresh air rate low
biological contamination	pollutant sources (building) (question 27) complaint areas near sources	early morning, Mondays, when fresh air rate low, summer
temperature	areas without a thermostat complaint areas	early mornings, late afternoons
humidity	supply air complaint areas	mornings, Mondays, midwinter, midsummer
air movement	near diffusers, exhaust complaint areas	doesn't matter

TABLE 2

Suitable Control Locations for Measuring Pollutants

Pollutant	Suitable control location
carbon dioxide	air intakes (if not contaminated) outdoors, street level or roof indoors, unoccupied area
carbon monoxide	air intakes (if not contaminated) outdoors, roof or upper floor indoors, above second floor
formaldehyde	air intakes (if not contaminated) outdoors, sheltered area (no wind or rain) indoors, lobby or reception area
particulates	air intakes (if not contaminated) outdoors, roof or upper floor on the building side of particulate filters indoors, unoccupied area
VOC	air intakes (if not contaminated) outdoors, street level or roof indoors, lobby or reception area
biological contamination	air intakes (if not contaminated) outdoors, roof indoors, area with no mould, no water, no plants

APPENDIX F

Data Assessment Table

POLLUTANT (measurement units)	MEASURED CONCENTRATIONS normal outdoor	normal indoor	possible problem	do not exceed
CARBON DIOXIDE (ppm)	330–400	330–800	800–1000	1000
CARBON MONOXIDE (ppm)	0–4	0–4	4–11	11
FORMALDE-HYDE (ppm)	0–0.02	0–0.1	0.05–0.01	0.1
NITROGEN DIOXIDE (ppm)	0–0.04	0–0.04	0.03–0.05	0.05
OZONE (ppm)	0–0.03	0–0.10	0.05–0.1	0.1

The measured values of temperature and relative humidity should also be compared to the ranges allowed by ASHRAE. These are:
winter temperature: 19.5–24.6°C;
summer temperature: 22.6–27.2°C;
winter humidity: 25–85%;
summer humidity: 25–70%

In regions with cold, dry winters and hot, damp summers, the humidity limits are effectively: not less than 25% RH in winter, and not more than 70% in summer.

If temperatures or humidities at the extremes of these ranges are recorded, this indicates a "possible problem." Measured values outside the extremes are effectively in the "do not exceed" column of the table.

For air movement in the occupied zone, average winter air movement should not exceed 0.15 m/s (30 fpm). Average summer air movement should not exceed 0.25 m/s (50 fpm).

APPENDIX G

Instrumentation for Simple Field Measurements

Pollutant/Cause	Equipment	Units of Measurement
Carbon Dioxide	Fuji ZFP5 Horiba APBA-210	PPM PPM
Carbon Monoxide	ISD C0260 Dynamation 104 Gastec Colorimetric Tube	PPM PPM
Formaldehyde	ATL Chemical Kit Pro-Tek Passive Dosimeter	PPM
VOC	Gastec Pump and Tubes	PPM
Relative Humidity (RH)	Vaisala HMI 31 HMP-31UT	%
Temperature (T)	Vaisala HMI 31 HMP-31UT	C or F
Air Movement	Gastec Smoke Tube Kit	none
Respirable Suspended Particulates (RSP)	MDA-PDC-1 Digital Dust Counter	mg/m

TABLE 1

Requirements	Outdoor Air Requirements cfm/person
Assembly Occupancies Intended for the Production and Viewing of the Performing Arts	
Motion picture theaters	15
Opera houses	15
Television studios admitting a viewing audience	15
Theaters, including experimental theaters	15
Other Assembly Occupancies	
Art galleries	15
Auditoria	15
Churches and similar places of worship	15
Clubs, nonresidential	15
Community halls	15
Court rooms	15
Day-care centers	15
Exhibition halls, other than in Group E	15
Gymnasia	15
Lecture halls	15
Libraries	15
Museums	15
Schools and colleges, nonresidential (excluding laboratories)*	15
Institutional Occupancies	
Jails	20
Penitentiaries	20
Police stations with detention quarters	15
Prisons	20
Psychiatric hospitals with and without detention quarters	15
Reformatories with detention quarters	15
Children custodial homes	15
Convalescent homes	15
Hospitals (excluding patient rooms and operating rooms)**	15
Infirmaries	15
Nursing homes	15
Orphanages	15
Reformatories without detention quarters	15
Sanitoria without detention quarters	15
Business and Personal Services Occupancies	
Banks	15
Offices	15
Police stations without detention quarters	15
Mercantile Occupancies	
Department stores	15
Exhibition halls	15

* Laboratories should have at least 25 cfm/person

NOTE: 15 cfm/person = 7.5 L/sec/person
20 cfm/person = 10 L/sec/person

** Patient Rooms and Operating Rooms should have at least 25 to 30 cfm/person

TABLE 2

Summary of Indoor Pollutants, Emissions Sources, and Concentrations (Spengler and Sexton 1983)

Pollutant	Major Emission Sources	Typical Indoor Concentrations in the Presence of Indoor Emission Sources	Indoor/ Outdoor Concentration Ratio ([5])
	Origin: predominantly outdoors		
Sulfur oxides (gases, particles)	Fuel combustion, smelters	0–15 ug/m^3	L
Ozone	Photochemical reactions	0–10 ppb	L
Pollens	Trees, grass, weeds, plants	L.V. ([1])	L
Lead, manganese	Automobiles	L.V.	L
Calcium, chlorine, silicon, cadmium	Suspension of soils, industrial emissions	N.A. ([2])	L
Organic substances	Petrochemical solvents, natural sources, vaporization of unburned fuels	N.A.	L
	Origin: indoors or outdoors		
Nitric oxide, nitrogen dioxide	Fuel burning	10–120 ug/m^3 ([3]) 200–700 ug/m^3 ([4])	VG
Carbon monoxide	Fuel burning	5–50 ppm	VG
Carbon dioxide	Metabolic activity, combustion	2000–3000 ppm	VG
Particles	Resuspension, condensation of vapours, combustion products	10–1000 ug/m^3	E
Water vapor	Biological activity, combustion evaporation	N.A.	G
Organic substances	Volatilization, combustion, paint, metabolic action, pesticides	N.A.	VG
Spores	Fungi, molds	N.A.	G
	Origin: predominantly indoors		
Formaldehyde	Particleboard, insulation, furnishings, tobacco smoke	0.01–0.5 ppm	G
Asbestos, mineral and synthetic fibers	Fire retardant materials, insulation	0–1 fiber/mL	E

TABLE 2

Summary of Indoor Pollutants, Emissions Sources, and Concentrations (Spengler and Sexton 1983)

Pollutant	Major Emission Sources	Typical Indoor Concentrations in the Presence of Indoor Emission Sources	Indoor/ Outdoor Concentration Ratio ([3])
Organic substances	Adhesives, solvents, cooking, cosmetics	L.V.	G
Ammonia	Metabolic activity, cleaning products	N.A.	G
Polycyclic hydrocarbons, arsenic, nicotine, acrolein, and so forth	Tobacco smoke	L.V.	VG
Mercury	Fungicides, paints, spills in dental-care facilities or labs, thermometer breakage	L.V.	G
Aerosols	Consumer products	N.A.	VG
Microorganisms	People, animals, plants	L.V.	G
Allergens	House dust, animal dander, insect parts	L.V.	VG

([1]) — LV, limited and variable (limited measurements, high variation)
([2]) — NA, not applicable
([3]) — annual average
([4]) — one-hour average in homes with gas stoves, during cooking
([5]) — L, less than 1; G, greater than 1; VG, very much greater than 1; E, equal to 1

SOURCE: Spengler and Sexton 1983)

(SOURCE: Nero 1988)

TABLE 3

Air Pollutant Criteria in ASHRAE Standards 62–1981 and 62–1981R

a) Criteria for Make-up Air (U.S. EPA):

Sulfur Dioxide	0.03 ppm (year);	0.14 ppm (24 hours)
Total particulate	75 ug/m^3 (year);	260 ug/m^3 (24 hours)
Carbon monoxide	9 ppm (8 hours);	35 ppm (1 hour)
Ozone	—	0.12 ppm (1 hour)
Nitrogen dioxide	0.055 ppm (year)	
Lead	1.5 ug/m^3 (3 months)	

b) Criteria for Indoor Air:

Standard 62–81:
Formaldehyde 0.1 ppm (0.12 mg/m^3)

Standard 62–81R:
Carbon Dioxide 1000 ppm (1.8 g/m^3)

Both:
Chlordane 0.0003 ppm (5 ug/m^3) (continuous)
Ozone 0.05 ppm (100 ug/m^3)

TABLE 4

Relationships Among Extent of Complaints Regarding Indoor Air Quality, CO_2 Levels and Ventilation Rates

Comments	CO_2 (ppm)	Ventilation Rate/Person CFM	Ventilation Rate/Person L/s
Occasional complaints, particularly if the air temperature rises	600	35	16.5
Complaints are more prevalent	800	21	10
Insufficient make-up air, complaints more general	1000	15	7

TABLE 5

The Conversion of Indoor Carbon Dioxide Levels to Effective Ventilation Rates

Carbon dioxide readings can be used to indicate effective ventilation rates in occupied buildings, according to the following approximate formula derived from ASHRAE Standard 62–1981:

Effective Ventilation Rate (in L/sec/person)
= 5000/([CO_2] ppm − 340)

(Note: 340 ppm is a typical ambient CO_2 level for downtown areas.)

Thus a CO_2 reading of 1000 ppm will require an effective ventilation rate = 5000/(1000 − 340) = 7.57 L/sec/person or 15.10 cfm/person.

TABLE 6

Occupational Limits for Selected Chemicals

Chemical	ACGIH 1/ mg/m³ (ppm)	Occ. Health & Safety Act — Ontario 2/ mg/m³ (ppm)
Acetaldehyde	180 (100) 270 (150)	180 (100) 270 (150)
Acrolein	0.25 (0.1) 0.8 (0.3)	0.23 (0.1) 0.7 (0.3)
Formaldehyde	1.5 (1) 3 (2)	1.5 (1) 3 (2)
Carbon dioxide	9000 (5000) 54,000 (30,000)	9000 (5000) 54,000 (30,000)
Carbon monoxide	55 (50) 440 (400)	40 (35) 460 (400)
Nitrogen dioxide	6 (3) 10 (5)	5.6 (3) 9.4 (5)
Sulfur dioxide	5 (2) 10 (5)	5.1 (2) 104 (5)

1/ American Conference of Governmental and Industrial Hygienists. The upper number represents time-weighted average threshold limit value; the lower, the short-term exposure threshold limit value.

2/ Occupational Health and Safety Act, R.S.O. 1980, c. 321. Ontario Regulation 654/86 as amended by Ontario Regulations 707/86.

The upper number represents time-weighted average exposure; the lower, the short-term exposure.

TABLE 7

Indoor Air Quality Guidelines (Prepared by the World Health Organization (WHO, 1984) Consensus of Concern about Indoor Air Pollutants at 1984 Levels of Knowledge

Pollutant [a]	Concentrations Reported [b]	Concentrations of limited or no concern [b]	Concentrations of concern [b]	Remarks
Tobacco smoke (passive smoking)				
• Respirable particulates	0.05–0.7	<0.1	<0.15	Japanese standard 0.15 mg/m³
• CO	1–1.5	<2	>5	Indicator for eye irritation (only from passive smoking)
• Nitros-dimethylamine	$(1–50) \times 10^{-6}$	—	—	Mutagens under investigation for carcinogenicity
NO_2	0.05–1	<0.19	>0.32	
CO	1–100	2% COHb <11	3% COHb >30	99.9% Continuous exposure
Formaldehyde	0.05–2	<0.06	>0.12	Long and short term
SO_2	0.02–1	<0.5	>1.35	SO_2 alone, short term
CO_2	600–9000	<1800	>12,000	Japanese standard, 1800 mg/m³
O_3	0.04–0.4	0.05	0.08	
Asbestos	<10 fibers/m³	0	10^5 fibers/m³	For long-term exposure
Mineral fibers	<10 fibers/m³	—	—	Skin irritation
Organics			(ug/m³)	
• Methylene chlorine	0.005–1	—	350 260	TLV [d] NIOSH [e] recommendations
• Trichloroethene	0.0001–0.02	—	270 135	TLV NIOSH recommendations
• Tetrachloroethene	0.002–0.05	—	335	TLV
• 1, 4-Dichlorobenzene	0.005–0.1	—	450	TLV
• Benzene	0.01–0.04		carcinogen	carcinogen
• Toluene	0.015–0.07	—	375	TLV
• m, p-Xylene	0.01–0.05	—	435	TLV
• n-Nonane	0.001–0.03	—	1050	ILO [f] (1980)
• n-Decane	0.002–0.04	—	—	
• Limonene	0.01–0.1	—	560	TLV turpentine

TABLE 7 (Continued)

Indoor Air Quality Guidelines (Prepared by the World Health Organization (WHO, 1984) Consensus of Concern about Indoor Air Pollutants at 1984 Levels of Knowledge

Pollutant [a]	Concentrations Reported [b]	Concentrations of limited or no concern [b]	Concentrations of concern [b]	Remarks

[a] All gases were considered on their own without other contaminants
[b] Typical ranges of concentration given in mg/m^3 unless otherwise indicated, and for short-term exposures
[c] According to Environmental Health Criteria No. 4, Geneva, World Health Organization, 1977
[d] TLV (threshold limit values) established by the American Conference of Governmental Industrial Hygienists (1983/1984). These values are for industrial exposures and should be considered as extreme upper limits for non-occupation populations for very short-term exposures.
[e] NIOSH — National Institute for Occupational Safety and Health U.S.A.
[f] ILO — International Labour Organization
— No meaningful numbers can be given because of insufficient knowledge

TABLE 8

Summary of Exposure Guidelines for Indoor Air Quality. Developed by a Working Group of the Federal/Provincial Advisory Committee on Environmental and Occupational Health (HWC 1987)

Contaminant	Some Possible Health Effects	Acceptable Exposure Ranges Aster ug/m^3 (ppm)	Alter
Aldehydes (total)	Eye, nose, throat irritation	$c_i/C_i<1$([1]) – 5m	—
Carbon Dioxide	Acidosis	–	<6300 (<3500)
Carbon Monoxide	Adverse effects on cardiovascular system	(<11) – 8 h ([2]) (<25) – 1 h ([2])	—
Formaldehyde		([3])	([3])
Nitrogen Dioxide	Respiratory disease; Respiratory irritation; Impaired lung function	<480 (<0.25) – 1 h	<100 (<0.05)
Ozone		<240 (<0.12) – 1 h	—
Particulate Matter ([4])		<100 – 1 h	<40
Sulphur Dioxide		<1000 (<0.38) – 5 m	<50 (<0.019)

[1] C_i = 120 ug/m^3 - formaldehyde; 50 ug/m^3 - acrolein; 9000 ug/m^3 - acetaldehyde, and c_i are respective concentrations measured over a 5-minute period.

[2] Units given only in parts per million so that guidelines are independent of ambient pressure.

[3] See Aldehydes (total). Since formaldehyde is considered a potential human carcinogen, every effort should be made to reduce exposure levels to the lowest possible level. The exposure guidelines are expressed in terms of what can be attained now, given as the action level 120 ug/m^3 (0.1 ppm) and what should be striven for air longer-term objectives, given as the target level 60 ug/m^3 or 0.05 ppm.

[4] <2.5 um mass median aerodynamic diameter.

TABLE 9

Standards and Guidelines for Ambient Air for Selected Chemicals.

Chemical	Federal 1/ ug/m^3 (ppb)	Ontario 2/ ug/m^3 (ppb)	US-EPA 3/ ug/m^3 (ppb)
Carbon monoxide	0 – 6000 – 8h 6000 – 15,000 – 8h	6000 15,000 – 8h	10,000 (9000) – 8h
Formaldehyde	—	65(50) 65 – 1h	—
Nitrogen dioxide	—	500 200 – 24h	100 (53) – annual arithmetic mean
Ozone	0 – 30 – 24th 30 – 50 – 24h	200 165 – 1h	235 (120) – 24h
Particulate matter	0 – 60 60 – 70	100 (d <44 um) 60 – 1 yr	150 – 24h (d <10 um)
Sulfur dioxide	0 – 30 30 – 60	830 55 – 1 yr	1300 (500) – 3

1/ The upper and lower ranges represent the desirable and acceptable values set by regulation under the Clean Air Act 1970-71-72, C-47. The numbers, unless stated otherwise, are annual arithmetic means. The geometric annual mean is used for particulate matter.

2/ The upper value is the point of impingement value, averaged over 30 m (Regulation 308, General-Air Pollution, RRO, 1980). The lower is the ambient air criterion, averaged over the given time periods.

3/ The first values are national primary and/or secondary air quality standards. Unless otherwise noted, they are the maximum concentration during the time periods stated which is not to be exceeded more than once per year. These are set under Section 109 of the Clean Air Act.

TABLE 10

Contaminants for Which Numerical Guidelines were not Set by Working Group on Indoor Air Quality [1/]

Contaminant	Some Possible Health Effects	Recommendation
Biological Agents	Infectious disease; allergies	Prevent excess humidity and condensation. Keep surfaces clear of dust. Keep stagnant water sources such as humidifier tanks clean, and occasionally disinfect them. Maintain a high standard of personal hygiene.
Consumer Products (chlorinated hydrocarbons, pest control products, product aerosols)	Damage to central nervous system, allergic reactions	Ensure adequate ventilation and observe any other precautionary measures described on the product label and in any accompanying information. Use pesticides only when absolutely necessary.
Fibrous Materials	Lung cancer; skin irritation	Minimize inhalation of, and skin contact with, mineral fibers during renovations and installation operations. Examine materials and products containing fibers periodically for signs of deterioration. Seek advice before removing or damaging any materials thought to contain asbestos.
Lead	Learning impairment; neurological disorders	Minimize exposure, especially of children, to lead of airborne origin by frequently cleaning contaminated surfaces.
Polycyclic Aromatic Hydrocarbons (PAHs)	Lung cancer	Ensure that any combustion systems are properly installed and maintained, and operated under conditions of satisfactory ventilation.
Tobacco Smoke	Lung cancer; sensory and respiratory irritation	Avoid any exposure to tobacco smoke.

1/ Armstrong et al. 1988.

TABLE 11

Control Measures for Indoor Air Pollutants

Ventilation: Dilution of indoor air with fresh outdoor air or recirculated filtered air, using mechanical or natural methods to promote localized, zonal, or general ventilation	Combustion by-products; tobacco smoke; biological agents (particles); organic substances, etc.	Local exhaust of emissions; air-to-air heat exchangers; building ventilation codes
Source removal or substitution: Removal of less hazardous materials or products	Organic substances; asbestiform minerals; tobacco smoke	Restrictions on smoking in public places; removal of asbestos and use of less volatile products
Some modification: Reduction of emission rates through changes in design or processes; containment of emissions by barriers or sealants	Organic substances; asbestiform minerals; combustion by-products	Containment of asbestos and volatile substances
Air cleaning: Purification of indoor air by gas adsorbers, air filters, and electrostatic precipitators	Particulate matter; combustion by-products; biological agents (particles)	Air cleaners to control tobacco smoke; ultraviolet irradiation to decontaminate ventilation air; formaldehyde sorbant filters
Behavioral adjustment: Reduction in human exposure through modification of behavior patterns; facilitated by consumer education, product labeling, building design, warning devices, and legal liability	Organic substances; combustion by-products; tobacco smoke	Smoke-free zones; architectural design of interior space; certification of materials for construction

(SOURCE: Spengler and Sexton 1983)

ABATEMENT OF ASPERGILLUS NIGER CONTAMINATION IN A LIBRARY

E.N. Light, CIH J.A. Coco, CIH A.C. Bennett K.L. Long

ABSTRACT

This case study documents a systematic attempt to locate and abate mold growth in a library that had been subject to a series of major roof leaks with employees complaining of building-related allergies. Work was completed in the following sequence: (1) exposure assessment, (2) evaluation of initial corrective measures, (3) identification of residual sources, (4) development of abatement specifications, (5) abatement monitoring, and (6) clearance sampling. Initial air samples revealed high fungal concentrations dominated by the mold, Aspergillus niger, *a sensitizer and opportunistic pathogen. Maintenance personnel subsequently conducted a typical mold/mildew clean-up including elimination of visible mold growth and disinfection of some surfaces. Retesting indicated that* Aspergillus niger *continued to dominate fungal air samples. Specialized cleaning contractor equipment was retained to complete the abatement program. After cleaning with a higher-efficiency vacuum cleaner,* all *surfaces were disinfected. Also, porous, contaminated materials were discarded and the HVAC system was cleaned. Air monitoring was conducted at strategic locations during the project to document mold counts in adjacent occupied areas. Final clearance of the work area was based on completion of abatement specifications which included all surfaces passing visual inspection and airborne fungal counts being less than outside with* Aspergillus niger *not dominating. These criteria were met within two weeks after completion of the clean-up. One year later, airborne fungal concentrations remained in the background range.*

INTRODUCTION

Although microbial contamination can be a major source of building-related illness, there is little guidance available to building managers for remediation. As a result, most attempts to address microbial contamination proceed with a "trial and error" approach.

Microbial evaluation remains one of the least precise areas of indoor air quality assessment. A variety of common environmental fungi and bacteria may be isolated from indoor air samples, with no clear distinction between background and "problem" concentrations (ACGIH 1987). Where unsanitary conditions develop in either mechanical equipment or interior surfaces, microbial growth can be amplified to the point where complaints by allergy-prone individuals become prevalent or more serious building-related illnesses occur (Burge 1988; Morey 1988). The most frequent complaints in buildings with relatively high airborne microbial concentrations generally involve allergic reactions. In relatively rare cases, severe sensitization can be induced in some individuals, resulting in conditions such as hypersensitivity pneumonitis. Elevated levels of some common environmental organisms may also cause infection in immunocompromised individuals. Microbial organisms that can be the source of such infections are known as opportunistic pathogens (Burge 1987; Burge 1988). General approaches for remediating microbial contamination presented in the literature include disinfecting, HEPA vacuum cleaning, discarding contaminated porous material, eliminating moisture sources, and lowering relative humidity (USDA 1980; Morey 1984).

This case study documents a systematic attempt to assess and control a large-scale mold growth problem in a library. The authors were retained as consultants to the facility—first to assess indoor air quality complaints and subsequently, to direct remediation. Present standards for the abatement of asbestos-containing materials were used as guidance in the establishment of work specifications. These were modified substantially to reflect unique aspects of microbial contamination.

The library under investigation is located in the Washington, DC, metropolitan area and is part of a 20-year-old educational facility of 160,000 ft² (14,857 m²). Of primary concern were the library and adjacent offices, which shared a common air handler. For purposes of this project, the space was subdivided into three zones (see Figure 1) as follows:

Zone 1: Library main room (approximately 5000 ft² (464 m²) and site of the most direct water damage).

Zone 2: Six library rooms adjacent to the main room (approximately 2000 ft, 186 m²).

Zone 3: Sixteen offices adjacent to Zone 2 (approximately 5000 ft², 464 m²).

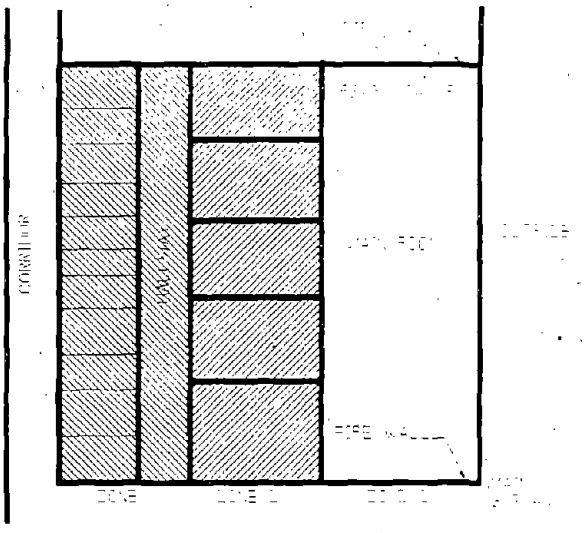


Figure 1 Library abatement project

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The sequence of events covered by this case study includes (in chronological order):

1. A series of major roof leaks occur in the library over a two-year period (until effective repairs are implemented).
2. Librarians complain of building-related illness.
3. Authors conduct microbial assessment.
4. In-house clean-up fails to eliminate complaints.
5. Detailed abatement process is designed by authors.
6. Remediation is conducted by an institutional cleaning contractor under supervision of authors.
7. Library meets clearance criteria and is reoccupied.
8. Testing is conducted one year later to determine long-term effectiveness.

METHODOLOGY

Assessment Strategy

Microbial sampling was preceded by a visual inspection of Zones 1 and 2, a limited scope evaluation of the HVAC system, interviews with operational staff, and a review of health questionnaires completed by librarians. Based on these preliminary findings, a sampling scheme was designed to provide a general characterization of airborne microbial concentrations and potential sources.

Initial Remediation

In-house maintenance personnel implemented typical building procedures for dealing with water incursion and subsequent mold growth. Initial efforts involved general cleaning of the affected area and repair of the roof. Employee complaints prompted further efforts, beginning with the authors' microbial assessment. While laboratory results were pending, facility management proceeded with a general mold/mildew clean-up of the area. This was accomplished by in-house maintenance and housekeeping personnel, with no special expertise involved in the effort. This work was restricted to surfaces within Zone 1 with visible growth. Specific actions included:

1. Removing mold stains on walls with a bleach cleaner.
2. Discarding moldy books.
3. Shampooing carpet with a disinfectant.
4. Damp-wiping some shelves and walls.
5. Installing a dehumidifier.

A reassessment of the library following completion of this work provided an evaluation of the effectiveness of a typical maintenance response to a building mold contamination problem. This, in effect, became a control for later comparison with the results of a more systematic abatement approach in the same area.

Abatement Strategy

Detailed specifications for abatement can be found in the appendix. Site-specific requirements were included for Zones 1, 2, and 3 HVAC equipment. Work was sequenced to minimize the recontamination of cleaned areas.

Containment involved sealing entries to adjacent areas with plastic. Cleaning utilized a higher efficiency vacuum cleaner (97% effective for the collection of 0.5 micron particles) followed by disinfection with a substituted phenolic solution (minimum contact time, 20 minutes). Porous materials considered to be contaminated were discarded to ensure that reservoirs of mold spores would not remain after cleaning. Air handlers and ductwork were treated as potential secondary sources of mold contamination. These were cleaned and disinfected to the extent that practical access was available. In addition, encapsulant was applied to insulation in the air handlers and diffuser boxes.

Monitoring Strategy

Abatement work was performed under the supervision of an industrial hygienist who was present during part of each shift to ensure that specifications were followed and to monitor microbial levels. Inspection duties included ensuring that dust was contained and that all porous contaminated materials were removed. Microbial sampling was limited to fungal counts only. Air sampling sites were located in corridors and offices adjacent to abatement areas to evaluate the effectiveness of containment precautions. Representative surface samples were collected in each area to determine the effectiveness of cleaning and containment. Immediately preceding abatement, baseline air and surface samples were collected as a reference to compare any changes documented during the abatement process.

Completion of the cleaning contractor's obligation and reoccupancy of the affected area was to be based on a formal clearance process similar to that used for asbestos abatement (US EPA 1985). Before final air sampling was permitted, the following criteria had to be met:

1. All abatement specifications were successfully completed.
2. All surfaces passed visual inspection.
3. Swabs of representative surfaces did not exceed background fungal concentration. Note: Lacking any guidelines for this parameter, the authors included 1000 CFU/in^2 in the performance criteria for this project to demonstrate that surfaces had been disinfected. Clean building surfaces are typically less than 1000 CFU/in^2 while swab samples in excess of this amount may be considered unsanitary or indicative of sources contributing to airborne microbial problems.

Airborne fungal samples were then collected at representative sites in the abatement areas along with a control outside the building.

Clearance generally required inside fungal concentrations to be less than outside. However, if the outside concentration was low on the day of sampling (less than 500 CFU/m^3), inside fungal counts would be allowed up to 500 CFU/m^3. Finally, *Aspergillus niger* could not dominate any of the samples in order for the work area to be cleared for reoccupancy.

Sampling and Analysis

All microbial sampling, along with subsequent counts and identification of organisms, generally followed standard methods (ACGIH 1987). The initial assessment phase also included systematic documentation of environmental conditions potentially related in microbial growth.

Air samples were collected with a single stage (N-6) viable impactor using Standard Methods Agar media for bacteria and Sabouraud Dextrose Agar for fungi in conjunction with a high-volume air sampling pump. Surface samples were collected with a sterile swab applied to a 2 in by 2 in area. Bulk samples (i.e., carpet) were collected with a sterile cutting tool.

All culture plates obtained from air sampling or the extraction of surface or bulk samples were incubated (3–7 days at 25°C for fungi or 2–3 days at 35°C for bacteria) and then colonies were counted. Taxa were identified in selected sam-

TABLE 1

Initial Assessment — Microbial Sampling Results

Location	Bacteria CFU/m³	Bacteria Type	Fungi CFU/m³	Fungi Type
(Air Samples)				
Zone 1	18	Bacillus sp. Corynebacterium sp.	1382	*Aspergillus niger* Aspergillus sp. Rhizomucor sp. Penicillium sp.
Zone 2 (Room A)	25	Bacillus sp. Corynebacterium sp.	654	*Aspergillus niger* Aspergillus sp. Penicillium sp.
Zone 2 (Room B)	231	Bacillus sp. Micrococcus sp. *Staph. epidermidis* Pseudomonas sp. Flavobacterium sp. Corynebacterium sp.	1026	*Aspergillus niger* Aspergillus sp. Pencillium sp.
(Surface Sample)				
			CFU/in²	Type
Zone 1 – Book			3.5×10^5	*Aspergillus niger* Aspergillus sp.

TABLE 2

Second Assessment — Fungal Sampling Results

Location	Airborne Fungi (CFU/m³)	Fungal Types
Zone 1 (rear)	85	*Aspergillus niger*
Zone 1 (front)	46	*Aspergillus niger*
Zone 1 (ceiling plenum)	71	*Aspergillus niger*
Zone 2 (Room B)	42	*Aspergillus niger*
Zone 3	83	*Aspergillus niger*
Adjacent Corridor (A)	165	Pencillium sp.
	Surface Fungi (CFU/in²)	
Zone 1 Bookshelf (clean)	8	Aspergillus sp.
Zone 1 Bookshelf (not clean)	4	*Aspergillus niger*
	Bulk Fungi (CFU/gm)	
Zone 1 (carpet)	5.6×10^4	*Aspergillus sp.*
Zone 2 (drape)	5.9×10^3	*Aspergillus sp.*

ples using standard medical microbiological isolation and characterization techniques.

RESULTS

Initial Assessment

Health questionnaires completed by the three employees permanently stationed in the library noted several symptoms that seemed to be occurring frequently at work in apparent association with the water leak problem. The symptoms, which were said to diminish upon leaving the building, included asthmatic attacks, sneezing, congestion, swelling, upper respiratory irritation, fatigue, and headaches. Although such symptoms are considered non-specific, they are generally consistent with the response of allergy-prone individuals to elevated levels of sensitizing molds. Personal physicians were said to suspect reported mold exposure in the work place as being responsible for the symptoms. No other significant emission sources or contaminants were observed in the library area by the authors. Although beyond the scope of this study, ventilation was later found to be deficient in the area and could have contributed to the headache and fatigue components of the complaints.

Interviews with building personnel revealed that major roof leakage had occurred intermittently in the rear of the main room over a two-year period and had been permanently repaired several months prior to the authors' investigation. Water-damaged ceiling tiles had also been replaced. An effort to shampoo the carpet may have exacerbated the problem due to incomplete extraction of the cleaning solution and lack of adequate ventilation. During the authors' initial inspection, damp furnishings and visible mold growth were noted in the rear of the main room. Mold was growing on the carpet, walls, shelves, and books. A mildew-like odor was present. Relative humidity was high, ranging from 72% to 78%.

Microbial test results are presented in Table 1. Airborne bacteria were considered to be in the background range and consisted of common environmental organisms. However, airborne fungi were consistently high (580 to 1300 CFU/m³) and were dominated by *Aspergillus niger*, a sensitizing mold and opportunistic pathogen. Elevated levels were found in both Zones 1 and 2 (the only areas tested initially). Visible growth on books contained high surface fungal counts (greater than 10^5 CFU/in²) also dominated by *Aspergillus niger*.

Initial Remediation (In-House)

Following a standard mold/mildew clean-up conducted by in-house maintenance staff (see Methodology), librarians continued to complain of building-related symptoms. The area was reassessed to identify remaining mold residues and to develop more specific recommendations.

Inspection indicated that exposed mold growth and mildew odor had been virtually eliminated. Dehumidification had reduced relative humidity to 55%. Cleaning had been

TABLE 3

Abatement Monitoring — Airborne Fungal Sampling Results in CFU/m³

Location	Project Day:	Base	One	Two	Three	Four	Five	Six
Zone 1		ND	—	—	—	—	—	807
Zone 2		269	—	1410	—	—	—	1355
Zone 3		163	1410	—	—	502	—	1084
Adjacent Corridor (A)		32	113	—	—	456	502	1873
Adjacent Corridor (B)		67	—	25	—	—	134	—
Outside Air		194	—	—	—	—	—	1679

Notes: Five pre-abatement surface samples ranged from ND-180 CFU/in².
Fifteen surface samples during abatement ranged from ND-3 CFU/in².

ND = not detected

TABLE 4

Clearance Samples (Day 18) — Fungal Sampling Results

Location	Airborne Fungi (CFU/m³)	Fungal Types
Zone 1	65	Cladosporium sp. Penicillium sp. *Mycelia sterilia*
Zone 2	189	Cladosporium sp. *Mycelia sterilia* Penicillium sp.
Zone 3	426	Cladosporium sp. Rhizomucor sp. Epicoccum sp.
Adjacent Corridor (A)	159	Cladosporium sp. Penicillium sp. Alternaria sp.
Outside Building	742	Cladosporium sp. Aspergillus sp. Fusarium sp.

only partially effective, with visible dust still observed on approximately 10% of the library shelf surface area. About 1% of the books showed signs of mold growth upon close examination. Inspection of the space also revealed mold growth behind baseboards and on insulation pads associated with air supply vents. Water stains and collected dust were noted in many luminaries (light coverings that also provided slots to the return air plenum). Two air handlers that had recirculated air from the contaminated zone were also examined. Internal surfaces, including insulation, were in need of cleaning.

More detailed microbial sampling was conducted at this time in order to better delineate the affected area and locate additional sources. Total airborne fungal counts were lower (42 to 85 CFU/m³). Although this may have reflected the use of disinfectants, it should be noted that the facility was virtually closed on the test day. Under quiescent conditions, microbial concentrations tend to be lower and may not be representative of levels occurring under higher occupancy. Samples dominated by *Aspergillus niger* were assumed to indicate areas affected by the mold problem. These occurred throughout Zones 1, 2, and 3, their boundaries coinciding with the areas served by one major air handler.

TABLE 5

One Year Follow-Up — Fungal Sampling Results

Location	Airborne Fungi (CFU/m³)	Fungal Types
Zone 1	110	Epicoccum sp. Penicillium sp. Cladosporium sp.

Air sampling conducted in the adjacent HVAC zone (main corridor) contained no *Aspergillus niger*. An air sample in the above-ceiling return air plenum in Zone 1 contained *Aspergillus niger* in the same amount as adjacent room air. This suggested that the plenum served to transmit, but not amplify, the contaminant. Diagnostic testing was also conducted on library carpet and drapes. These were found to contain elevated mold counts, suggesting that porous materials continued to collect, grow, and release mold in the area of concern. Surface swabs of shelves revealed that *Aspergillus niger* was present, but at low amounts. This suggested that hard surfaces were less significant sources than porous materials and had been (at least temporarily) disinfected to a background level. Results of the second sampling phase can be found in Table 2.

Comprehensive Abatement

Systematic cleaning, disinfection, or removal of mold sources was accomplished by a commercial cleaning contractor (specializing in fire and water restoration and hospital maintenance) over a seven-day period. The specifications were followed in detail (see Appendix). Work proceeded from the most contaminated to the least contaminated areas and, within a given space, from top to bottom. The HVAC system remained off and occupants were excluded from the work areas. Plastic barriers were maintained at entries to adjacent spaces with smoke tube observations indicating work areas were either neutral or negatively pressured. Twelve thousand library books were examined. About 1% were discarded due to visible mold growth with the remainder of the books HEPA vacuumed and placed in temporary storage. Carpet removal appeared to be the operation with the greatest potential for spore release and was accomplished with minimal airborne dust generation. Disinfection contact time complied with specifications and was followed by protection of cleaned surfaces from recontamination.

Results of monitoring conducted during abatement can be found in Table 3. Air quality in active work areas was not measured (due to a focus on protecting occupied areas). Airborne fungal counts in Zones 2 and 3 ranged from 502–1410 CFU/m³. Readings in the adjacent HVAC zone remained at background levels for the first four work days, then rose to 1873 CFU/m³ on day five. Final cleaning was completed on day six. Air samples collected in the work areas two hours after completion of work remained elevated (807 to 1355 CFU/m³), apparently reflecting the disturbance caused by the cleaning process. Surface samples collected from cleaned surfaces and in adjacent zones during the abatement period all had low fungal counts.

Final Clearance

Final testing was delayed in order to let the space achieve equilibrium under the new conditions. With major mold sources apparently controlled, time was needed for air exchange, filtration, and settling to reduce airborne concentrations created by the recent disturbance. Final air tests were conducted on day 18 of the project (see Table 4). Samples from Zones 1, 2, and 3 now contained no *Aspergillus niger*, with counts reflecting normal background levels. Results met all clearance criteria including inside counts (65 to 426 CFU/m³) lower than outside (742 CFU/m³). A review of surface sampling data and visual inspections also indicated that all abatement obligations had been met. Under these conditions, the library was reopened.

Follow-Up Testing

One year after the abatement project, the library was retested for airborne fungi to evaluate the long-term effectiveness of the procedure utilized. In some microbial decontamination projects, only temporary reductions are achieved and conditions promoting renewed growth reoccur.

A single air sample was conducted in the worst-case location (Zone 1) under typical occupied conditions. Airborne fungi remained in the low background range (110 CFU/m³) and did not contain *Aspergillus niger* (see Table 5). This limited sampling suggests that air quality had remained stable over a one-year period.

DISCUSSION

Although this investigation is reported as a case study, certain observations may provide general guidance for the implementation of similar projects.

Interpretation of Microbial Results

Microbial sampling results are subject to wide variability and cannot be compared to precise standards or action levels (ACGIH 1987). The decision-making process that led to a determination that airborne mold levels posed an immediate problem in the library was as follows:

1. Preliminary inspection revealed major water incursion and obvious microbial growth.
2. All airborne fungal counts were above 500 CFU/m³ (upper limit of the typical range found in "non-problem" buildings based on the authors' experience).
3. All samples were dominated by a mold not common in outside air and known to be an opportunistic pathogen.
4. Health questionnaires indicated that employees were experiencing allergenic symptoms consistent with exposure to microbial sensitizers in the workplace.

Developing the scope of work for microbial remediation requires the delineation of boundaries for the contaminated area and the identification of microbial reservoirs which are contributing to elevated airborne levels. In this assessment, rooms were categorized into apparent homogeneous areas based on visual inspection, history of water incursion, and ventilation. Limited sampling was then conducted to help estimate relative contamination within each area. Following this approach, Zone 1 was concluded to be most contaminated, while Zones 2 and 3 were assumed to be contaminated to a lesser degree. Other building areas were considered to be not affected. Microbial reservoirs were similarly located (or assumed) by a combination of visual inspection, building history, and sampling. Moist interior surfaces appeared to be the original or primary source of mold growth. Secondary sources were considered to be porous materials that had contacted mold-contaminated air. Primary sources included books, ceiling tiles, and carpets, while secondary sources included drapes and HVAC insulation.

The influence of building activity on microbial sampling results may be an important consideration when conducting an environmental assessment. On the second sampling visit to the library, the facility was essentially closed and airborne mold counts dropped sharply. Occupant complaints persisted through this period and subsequent measurements were elevated. Although this temporary reduction was partly attributed to the partial clean-up conducted by in-house personnel, the lack of air movement and surface disturbance may have also been important factors. As a precaution, in subsequent projects the authors have attempted to either conduct airborne microbial sampling under typical activity conditions or use aggressive sampling techniques (i.e., operate a fan in the area to simulate occupant activity).

Laboratory turnaround time for abatement monitoring was three to five days. This raised questions as to what role microbial sampling could play in day-to-day decisions on the project. In contrast, turnaround time for fiber counts in asbestos abatement projects can be as short as one hour, allowing for rapid adjustments in the event that problematic levels are detected. In the library project, decisions on the adequacy of containment were based on observations of the industrial hygienist (i.e., compliance with specifications, integrity of barriers, presence of dust, or odor outside work area). Daily microbial counts provided documentation of project conditions after the fact. If the project had been continued beyond six days, adjustments would have been made based on elevated readings in adjacent areas. In subsequent projects involving demolition of materials with microbial contamination, the authors have used direct reading instrumentation for the measurement of respirable suspended particulates (RSP) as a surrogate for microbial levels. Elevated RSP are then assumed to be an indicator of microbial contamination escaping the containment. It should be noted that, in the absence of significant demolition dust, RSP may not be a good surrogate for airborne microorganisms. Microscopic examination of spore traps might provide another approach for monitoring microbial abatement projects.

In retrospect, the results of surface sampling were not critical in documenting progress on this project. Once disinfection efforts were initiated, swab samples of surfaces were consistently in the background range. In subsequent projects, the authors have placed lower emphasis on surface sampling.

The clearance of microbial abatement projects is a subject that has received little attention. Even well-controlled demolition and cleanup work can generate high microbial exposure levels. Before safe reoccupancy can be assured, a

period of time is needed for airborne microorganisms temporarily released during the abatement process to diminish to a new equilibrium level. Analysis of air samples may require another several days. Setting clearance criteria for microbial abatement is difficult due to the wide variation of background fungi and bacteria (generally less than 500 CFU/m^3) and the influence of outdoor levels. In this project, the primary clearance goal was for inside counts to be less than outdoor counts. If outdoor levels were low on the day of sampling, a secondary goal of 500 CFU/m^3 was acceptable. These criteria were based on the author's judgment as to a reasonable level of control that could be achieved with a microbial abatement project which would also provide a reasonable level of certainty that background levels would be maintained in the project area.

Abatement Specifications

In recent years, minimum standards for the demolition of asbestos-containing materials have been clearly defined (US EPA 1985). These include worker protection, containment, dust control, clean-up, and air quality. With similar, micron-range particles to consider, the demolition of materials heavily contaminated with mold or bacteria would appear to necessitate many of the same precautions. Fundamental differences with the asbestos model include lower health risks (if organisms are nonpathogenic) and the need for disinfection. At the present time, there are no requirements for microbial abatement and no detailed guidance is available.

Preliminary, in-house cleaning efforts to control the library mold problem were not effective in this case study for a variety of reasons, including the following:

1. The extent of the clean-up area was based on visible microbial growth, representing less than half of the area later found to be contaminated.
2. Disinfection was not conducted systematically, leaving some surfaces contaminated.
3. The cleaning of porous, heavily contaminated materials (carpets, drapes, books, etc.) was ineffective and these items needed to be replaced.
4. With a lack of containment, mold spores disturbed by the cleaning efforts are likely to have been disseminated to surrounding areas.

The subsequent comprehensive abatement effort was based on a detailed identification of microbial reservoirs and systematic procedures and proved to be much more effective than the in-house response.

One potential problem noted during the abatement project was elevated fungal counts outside the work area. This might have been controlled by placing the work area under a stronger negative pressure (the library was actually neutral to the rest of the building during much of the work). More complete containment and increased negative pressure would have the dual advantage of preventing leakage and cleaning air at the work site. While air exhausted from asbestos containments must be HEPA filtered, the direct discharge of nonpathogenic molds or bacteria by fans to the outside environment may be acceptable.

Personal protection was not a significant issue during the project. Although half-face respirators with HEPA filters were recommended, most workers and inspectors wore simple dust masks without any discomfort. More protective measures would have been needed for persons who were allergy-prone or immunocompromised.

The precautions needed for implementing other microbial abatement projects might be more or less stringent than those followed in this case study based on site-specific factors such as the following:

1. Types and numbers of organisms involved.
2. Scope of work and areas affected.
3. Magnitude of disturbance involved.
4. Proximity of occupants.
5. Sensitivity of occupants.

CONCLUSIONS

1. The library investigated had a significant microbial contamination problem, as reflected in high airborne concentrations of *Aspergillus niger*.
2. Initial in-house clean-up efforts were not successful because of a failure to identify and remove or disinfect all reservoirs of mold growth.
3. A detailed abatement effort permanently reduced airborne fungal counts to background levels and eliminated *Aspergillus niger* from subsequent air samples (see Figure 2).

RECOMMENDATIONS

Guidance is needed for conducting large-scale microbial abatement projects. Flexible standards are needed which allow such work to be implemented effectively and safely while accounting for a broad range of site-specific conditions. Experience in this case study suggests that special attention will be needed when developing standard procedures for the following areas:

1. Determining contamination boundaries and identifying reservoirs of microbial growth.
2. Containing and ventilating work areas.
3. Cleaning, disinfecting, or replacing contaminated surfaces.
4. Monitoring active abatement areas (including visual inspection, direct-reading instrumentation, and microbial sampling).
5. Clearance criteria.

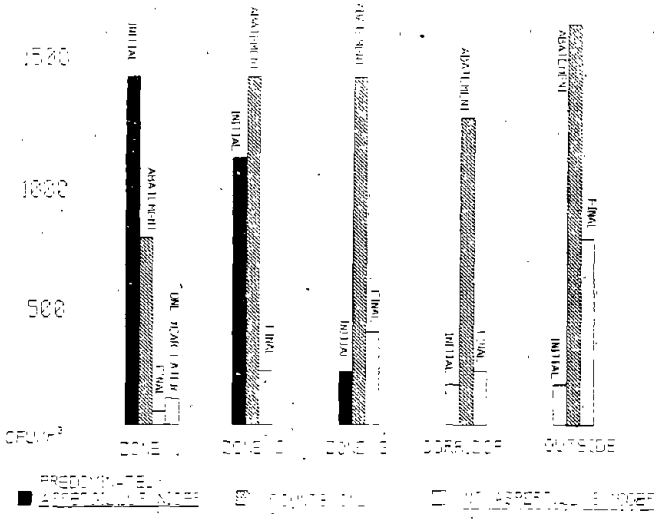

Figure 2 Comparison of peak fungal counts

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APPENDIX

Specifications Used for the Cleaning and Disinfection of Mold-Contaminated Library

Zone 1

1. Clean and disinfect Room A according to Zone 2 procedures, as indicated below.
2. HEPA vacuum all computer equipment, readers, and similar electronic equipment thoroughly; move into Room A and wrap in plastic sheet.
3. HEPA vacuum all audio/visual equipment in the audio/visual room.
4. HEPA vacuum all books in library. Start with books at east end and work to west end of room. Each book should be opened first to look for visible signs of mold. Those in this condition should be placed in a designated box for further action later. Those not showing visible signs of contamination should be packed in a box after vacuuming.
5. Prior to handling the library's drapes and carpet, the room must be secured to prevent unauthorized entrance and to minimize the likelihood of cross-contamination by the following procedure:
   a. Remove all drapes from Zone 2 offices and carefully place in plastic bag (see step 6 below).
   b. Seal all doors from the library side with plastic sheeting, except Room B, which will be used by designated individuals as an entrance and exit.
   c. HEPA vacuum the floor of Room B at least twice a day.
   d. Test the airflow differential between the library and adjacent areas to help ensure that the room is operated under one of two conditions: neutral or negative pressure to the surrounding public spaces. Ventilation smoke tubes will be used for this determination. Both air handlers will be shut down and made inoperable during this phase.
6. Remove drapes carefully from library and immediately place in plastic bags. Seal immediately to minimize dissemination of spore clouds.
7. Remove carpet in sections starting with east side of room first. Seal carpet section in plastic sheeting immediately.
8. Remove all plastic-bagged curtains and plastic-wrapped carpeting from the library through window. Wait approximately 2 hours settling time before proceeding with step 9.
9. Remove ventilation grilles; clean and disinfect with a combination detergent/disinfectant product containing a substituted phenolic-type disinfectant at the maximum use dilution recommended by the manufacturer; discard insulating pad associated with each air supply vent; HEPA vacuum ventilation supply ducts to the distance practical.

NOTE: Disinfectants typically take 20 to 30 minutes of *wet* contact time to achieve the desired level of disinfection. All disinfected surfaces should remain visibly wet for at least 20 minutes. Follow with clean water rinse if indicated by product manufacturer. Wipe up excess or standing water.

10. Remove all luminaries from the light fixtures; clean and disinfect using combination detergent/disinfectant, as indicated above.
11. HEPA-vacuum the ceiling.
12. HEPA-vacuum all walls or wall hangings.
13. HEPA-vacuum the floor.
14. Spray the floor with substituted phenolic disinfectant at indicated maximum use dilution.
15. HEPA-vacuum, then clean and disinfect all book shelves and furniture.

Zone 2

1. Remove all plastic sheeting from doors.
2. Remove all luminaries from the light fixtures; clean and disinfect as indicated.
3. Remove ventilation grilles; clean and disinfect as indicated; discard insulating pads; HEPA vacuum ventilation supply ducts as far as practical.
4. HEPA-vacuum all exposed horizontal surfaces.
5. Clean and disinfect floors using wet mopping technique for hard floors and disinfect carpet using disinfectant carpet shampoo. All disinfectant products will be of the substituted phenolic type.

Zone 3

1. Remove all stained or soiled luminaries from the light fixtures; clean and disinfect as indicated.
2. Follow steps 3 through 5 as indicated for Zone 2.

Air-Handling Equipment

1. Seal off the supply ducts of both AHUs prior to start of cleaning/disinfecting procedures.
2. Turn off units and lock out activation controls. Open AHUs carefully and without banging hatches (or covers) and ductwork to minimize aerosolization of microbes.
3. Carefully remove debris and filters by appropriate means.
4. Use the detergent/disinfectant product, as previously specified to thoroughly saturate (by low-pressure spray action) the entire interior of the unit including coil, condensate pan, fan and housing, filter rack, and insulation. Inaccessible insulation should be thoroughly saturated with the detergent/disinfectant. Be sure to spray any dampers (both sides) that are accessible in the unit. Follow with clean water rinse. Wipe or wet-vacuum excess or standing water.
5. Pressure-clean coils with an appropriate coil cleaner product using the least amount of pressure possible and still

achieve desired results. Wipe or wet-vacuum standing liquid in the AHU.

6. Encapsulate accessible insulation inside air handlers with an appropriate sealant.
7. Remove diffuser boxes associated with each air supply vent. Clean, disinfect, and encapsulate inside surfaces.

DISCUSSION

James V. Dirkes II, University of Michigan, Ann Arbor, MI: How many books were discarded and what percentage of the overall improvement do you attribute to that action?

E.N. Light, Biospherics Inc., Beltsville, MD: Approximately 200 books with visible mold growth were discarded from the library. Their precise contribution to airborne mold concentrations (as compared to carpets, insulation, and other surfaces) could not be determined.

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: After all the work and testing were completed, did you increase the outside air requirements of this facility?

Light: Although not specifically measured during the initial study, ventilation deficiencies probably contributed to the moisture/mold problem. Ventilation appeared to be increased due to the cleaning of air handler coils during the project. As a follow-up measure, HVAC controls were repaired and the system was balanced.

Marian Heyman, Hartford Steam Boiler, Hartford, CT: If valuable book materials were present in the library, was consideration given to sterilizing these materials with an ethylene oxide autoclave?

Light: In this situation, no rare books were present and all contaminated volumes could be replaced. For more specialized holdings, sterilization would have been considered.

PREVALENCE OF HEALTH AND COMFORT COMPLAINTS OF OFFICE WORKERS: MALE AND FEMALE DIFFERENCES

S.R. Kleven, M.Sc. T.D. Sterling, Ph.D.

ABSTRACT

A number of studies of the prevalence of reported health symptoms and environmental satisfaction among male and female office workers have found that females have a higher prevalence of health symptoms and are more dissatisfied with their working environment than males. In order to determine (1) whether or not there are sex differences in health and comfort complaints, and (2) whether or not these differences can be accounted for by age and job type, questionnaire responses given by 1760 office workers in seven separate buildings for 22 perceived health symptoms and 19 environmental indicators were analyzed. Chi-square analyses found sex differences for 21 of the health symptoms and 15 of the environmental perception indicators. With the exception of one environmental perception indicator, these differences could not be accounted for by age or job type. While clerical workers have the highest prevalence of health symptoms and are the least satisfied with their environment, they have the smallest difference in prevalence of health and comfort complaints between sexes. These results indicate that sex is a confounding factor for the perceived health and comfort of office workers; hence, it should be controlled for in all building-illness studies.

INTRODUCTION

A number of studies have investigated buildings in which occupants had complained about their health and the quality of the indoor environment. Some of these studies that compared the sexes with regard to the prevalence of health and comfort complaints found that females report more health problems and are less satisfied with their work environment than males (Finnegan and Pickering 1987; Hedge 1984a, b; Hedge et al. 1987; Honeywell Technalysis 1984; Woods et al. 1987). Possible causes for the observed differences between males and females are: (1) differences in working conditions, (2) differences in sensitivity to building-related illnesses, and (3) differences in psychosocial characteristics.

Between 1985 and 1987, seven buildings located in Canada, England, and the United States were investigated in response to employee complaints of poor air quality. Occupants of the seven buildings were asked (1) if they had experienced a range of health-related symptoms; (2) how they perceived characteristics of their ambient environment; and (3) questions about their personal characteristics, work environment, and job requirements.

In this paper, the data collected from the seven buildings are used to determine whether or not there are sex differences in the perceived health and comfort of these office workers, and whether or not these differences can be accounted for by age and/or job type.

METHODS

Between 1985 and 1987, a self-administered "Office Workers Environment Survey" (OWES) questionnaire was completed by the 1760 occupants of seven buildings. The occupant response rates ranged from 65% to 80%. These were full-time employees between the ages of 18 and 65 who were either clerical, professional/technical, or management workers.

Data were collected on the prevalence of experiencing 22 health-related symptoms (e.g., eye, nose, or throat irritation), and 19 environmental satisfaction indicators (e.g., temperature just right, too little air movement, too much noise) while in the work environment. (The health and environmental questions are listed in the appendix.) The answers to these questions were restricted to "never," "rarely," "sometimes," or "always." For the purpose of our analyses, the prevalence of health symptoms and environmental satisfaction was determined by (1) combining "sometimes" and "always" into a "yes" response and "never" and "rarely" into a "no" response and 2) calculating the percent of "yes" responses of the total number of responses ("yes" and "no" combined).[1] Chi-square analysis was used to determine if there were differences in the perceived health and comfort between male and female office employees. The Mantel-Haenszel chi-square analysis was used to determine if there were differences after adjusting for age and job type.

The difference in prevalence of health and comfort complaints between female and male office workers was expressed as a "sex ratio"—the ratio of female to male prevalence.

[1]The four-point response scale was transformed into a two-point scale because there were too few male and female "always" responses for statistical analysis.

TABLE 1

Distribution of Female and Male Office Workers by Job and Age Categories

	Female (#)	Male (#)
Job		
Management	79	188
Professional/Technical	229	571
Clerical	573	125
Age		
18–25	234	126
26–35	277	247
36–45	177	242
46–55	129	186
56–65	64	83

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RESULTS

The distribution of the study population by sex, age, and job type is shown in Table 1. Of the employees questioned, 49.9% were female; 65% were in clerical occupations, 26% in professional/technical, and 9% in management. Of the male respondents, 14.1% were in clerical occupations, 64.6% in professional/technical, and 21.3% in management. The age distribution differed substantially by sex, with the majority of females between 18 and 35 years of age, and the majority of males between 26 and 45 years of age.

Table 2 shows (1) the prevalence of health symptoms for females and males, and (2) the unadjusted as well as age- and job-type-adjusted sex ratios. Female office workers showed greater prevalence than males for 21 health symptoms. The prevalence of only one health symptom did not differ between the male and female office workers (difficulty concentrating).

The unadjusted sex ratio ranged from 1.32 to 3.42 for the health symptoms that showed significant differences in prevalence rates. Cold extremities, nausea, dizziness, skin dryness, chest pain, muscle ache, weakness, and neckache had the largest sex ratios.

The age-adjusted sex ratios did not differ by much from the unadjusted ratios. On the other hand, the job-adjusted sex ratios were substantially smaller for 12 of the 21 health symptoms that showed greater prevalence in females than males. After adjusting for job type, however, there still remained a significant difference in prevalence between female and male office workers for the 21 health symptoms.

Table 3 shows the prevalence of dissatisfaction, and the unadjusted and age- and job-type-adjusted sex ratios for 19 environmental factors. Females expressed greater dissatisfaction than males for 15 of the 19 environmental factors. The unadjusted sex ratios for environmental factors that showed differences between females and males ranged from 1.08 to 2.17 and from 0.75 to 0.56. The largest unadjusted sex ratios were associated with too little noise, too much air movement, temperature just right, and air moisture just right.

The age-adjusted sex ratios for too little noise and too much air moisture showed a substantial increase and decrease, respectively, from the unadjusted ratios. The remaining 13 age-adjusted sex ratios were the same or changed only slightly from the unadjusted ratios—the difference being no more than 7%. The job-adjusted sex ratios were lower for all environmental factors that showed a difference in prevalence between males and females. The job-adjusted sex ratios for too much air movement, too much light, too little noise, stuffy air, and odors showed substantial decreases from the unadjusted sex ratios, whereas the sex ratios for the remaining nine environmental factors did not decline by more than 18%. After adjusting for job type, the prevalence of experiencing high temperatures was the same for both sexes.

DISCUSSION

There appear to be sex-related differences in the prevalence of health symptoms and the perception of environmental indicators, with females reporting a higher prevalence of health symptoms and more dissatisfaction with their working environment than males. Although the age distribution of the sexes differed (males tended to be older than females), adjustment for age had little effect on the sex ratio.

TABLE 2

Prevalence of Health Symptoms and Unadjusted and Age and Job-Type Adjusted Sex Ratios

Health Symptoms	F[1]	M[2]	Unadjusted SR[3]	Age Adjusted SR	Job Adjusted SR
Headache	79.3	53.4	1.49*	1.46*	1.44*
Fever	11.5	5.4	2.13*	2.10*	1.53*
Cold/Flu	55.3	36.6	1.51*	1.48*	1.40*
Nausea	25.2	9.0	2.80*	2.70*	2.11*
Dizziness	30.9	12.9	2.40*	2.39*	2.14*
Respiratory Problems	17.3	8.9	1.95*	2.04*	1.58*
Chest Pain	14.8	6.5	2.26*	2.30*	2.01*
Eye Irritation	60.0	43.5	1.38*	1.38*	1.30*
Throat Irritation	54.8	37.9	1.45*	1.46*	1.42*
Nose Irritation	48.7	36.9	1.32*	1.31*	1.25*
Dry Skin	43.8	18.7	2.34*	2.36*	2.05*
Muscle Ache	31.8	14.2	2.24*	2.28*	1.86*
Backache	54.3	28.1	1.93*	1.90*	1.65*
Neckache	53.0	26.2	2.02*	2.03*	1.76*
Depression	32.1	17.9	1.79*	1.84*	1.48*
Tense	43.7	28.9	1.51*	1.57*	1.37*
Difficulty Concentrating	52.6	51.7	1.02	1.02	1.05
Fatigue	75.8	56.8	1.33*	1.32*	1.25*
Weakness	27.0	12.5	2.15*	2.04*	1.70*
Sleepiness	73.8	55.6	1.33*	1.30*	1.22*
Trouble Focusing	47.8	33.3	1.44*	1.44*	1.34*
Cold Extremities	56.3	16.5	3.42*	3.44*	2.96*

[1] Prevalence of female health symptoms. The percent of female YES responses to the total number of female responses.
[2] Prevalence of male health symptoms. The percent of male YES responses to the total number of male responses.
[3] Sex ratio. The ratio of the prevalence of health symptoms between female and male office workers.
* Significant difference in the prevalence of health symptoms between female and male office workers.

TABLE 3

Prevalence of Environmental Dissatisfaction, and Unadjusted and Age and Job-Type Adjusted Sex Ratios

Environmental Perception Indicators	F[1]	M[2]	Unadjusted SR[3]	Age Adjusted SR	Job Adjusted SR
Air Movement:					
Too Little	87.9	76.4	1.15*	1.15*	1.12*
Too Much	30.1	15.6	1.93*	2.10*	1.68*
Just Right	29.5	48.5	0.61*	0.63*	0.66*
Air Moisture:					
Too Little	89.0	75.5	1.18*	1.16*	1.13*
Too Much	10.9	10.3	1.06	1.00	0.97
Just Right	28.4	50.1	0.57*	0.59*	0.62*
Temperature:					
Too Hot	68.9	63.7	1.08*	1.08*	1.05
Too Cold	76.3	47.5	1.61*	1.57*	1.47*
Just Right	37.4	66.4	0.56*	0.58*	0.65*
Light:					
Too Bright	50.3	33.0	1.53*	1.46*	1.23*
Too Dim	23.9	23.4	1.02	1.02	1.03
Glare	60.1	41.2	1.46*	1.45*	1.28*
Just Right	47.4	63.1	0.75*	0.77*	0.83*
Noise:					
Too Much	70.6	69.9	1.00	1.02	1.03
Too Little	15.1	7.0	2.17*	1.88*	1.69*
Just Right	60.0	56.0	1.07	1.05	1.08
Air:					
Smoky	41.1	29.3	1.40*	1.42*	1.30*
Stuffy	87.8	75.1	1.17*	1.16*	1.12*
Odors	56.5	35.5	1.59*	1.59*	1.32*

[1] Prevalence of female environmental dissatisfaction. The percent of female YES responses to the total number of female responses.
[2] Prevalence of male environmental dissatisfaction. The percent of male YES responses to the total number of male responses.
[3] Sex ratio. The ratio of the prevalence of environmental dissatisfaction between female and male office workers.
* Significant difference in the prevalence of environmental dissatisfaction between female and male office workers.

TABLE 4

Prevalence of Health Symptoms of Female and Male Clerical, Professional/Technical, and Management Office Workers

Health Symptoms	Management		Professional/Technical		Clerical	
	F[1]	M[2]	F[1]	M[2]	F[1]	M[2]
Headache	77.2*	50.5	80.6*	53.0	79.1*	59.3
Fever	5.1	4.4	9.5*	4.8	13.3	9.9
Cold/Flu	52.6*	33.7	49.8*	36.4	57.9*	41.8
Nausea	19.5*	5.9	22.3*	8.3	27.2*	16.7
Dizziness	24.1*	13.0	31.1*	11.9	31.8*	17.2
Respiratory Problems	17.7*	7.6	15.8*	8.0	17.8	15.0
Chest Pain	16.5*	4.8	12.6*	6.7	15.4	8.5
Eye Irritation	61.0*	43.8	59.9*	41.5	59.9	52.5
Throat Irritation	60.8*	39.5	50.0*	37.2	55.9*	38.7
Nose Irritation	58.2*	33.3	45.8*	36.9	48.6	4.0
Dry Skin	43.0*	18.9	37.1*	17.4	46.6*	24.2
Muscle Ache	34.6*	8.6	26.1*	14.4	33.7*	21.5
Backache	52.6*	19.4	47.3*	28.5	57.4*	39.7
Neckache	57.0*	23.2	44.9*	25.1	55.7*	35.8
Depression	32.5*	14.6	25.3	17.2	34.8	26.2
Tense	50.6*	26.6	41.6*	27.3	43.5	39.3
Difficulty Concentrating	61.0	47.8	54.4*	53.3	50.7	50.4
Fatigue	82.3*	58.4	78.9*	52.6	73.7	73.8
Weakness	24.7*	8.6	22.8*	12.0	29.0	20.8
Sleepiness	69.6*	51.4	74.3*	53.4	74.1	72.1
Trouble Focusing	49.4*	28.0	42.0*	34.0	50.0*	37.7
Cold Extremities	59.5*	13.4	42.7*	16.5	61.4*	20.8

[1] Prevalence of female health symptoms. The percent of female YES responses to the total number of female responses.
[2] Prevalence of male health symptoms. The percent of male YES responses to the total number of male responses.
* Significant difference in the prevalence of health symptoms between female and male office workers.

TABLE 5

Prevalence of Environmental Dissatisfaction of Female and Male Clerical, Professional/Technical, and Management Office Workers

Environmental Perception	Management F[1]	Management M[2]	Professional/Technical F[1]	Professional/Technical M[2]	Clerical F[1]	Clerical M[2]
Air Movement:						
Too Little	87.3*	73.1	83.8*	76.8	89.7*	79.2
Too Much	27.3*	16.3	25.3*	14.3	32.5*	20.2
Just Right	30.8*	53.5	34.1*	48.1	27.5*	42.7
Air Moisture:						
Too Little	90.8*	76.6	87.3*	73.1	89.5	84.8
Too Much	3.9	11.0	10.9	9.9	11.9	11.2
Just Right	30.4*	54.1	33.2*	50.3	26.1*	43.2
Temperature:						
Too Hot	69.2	61.6	68.9	62.9	68.9	70.4
Too Cold	77.2*	45.7	66.2*	46.2	80.2*	56.0
Just Right	44.9*	70.3	46.2*	67.7	32.7*	54.8
Light:						
Too Bright	41.0*	28.6	43.4*	30.1	54.5	52.0
Too Dim	27.3*	16.2	27.2	25.0	22.1	27.2
Glare	54.5*	36.9	48.9*	40.5	65.5*	50.4
Just Right	59.7*	72.4	50.2*	62.8	44.5	50.4
Noise:						
Too Much	70.9	67.7	73.0	71.2	69.5	67.2
Too Little	5.2	3.8	11.5	7.4	18.0*	9.7
Just Right	57.0	64.1	60.7	55.5	59.1	56.8
Air:						
Smoky	28.6	24.5	43.0*	29.5	42.0	35.5
Stuffy	84.2*	71.0	88.5*	74.4	88.1	84.7
Odors	51.3*	33.5	47.1*	32.6	61.1	51.6

[1] Prevalence of female environmental dissatisfaction. The percent of female YES responses to the total number of female responses.
[2] Prevalence of male environmental dissatisfaction. The percent of male YES responses to the total number of male responses.
* Significant difference in the prevalence of environmental dissatisfaction between female and male office workers.

The ratio of females to males in each of the three job categories also differed: a higher proportion of females than males were clerical workers, whereas a higher proportion of males than females were managers. After adjusting for job type, the differences between sexes were removed for one environmental factor and reduced for 13 health symptoms and 5 environmental factors. These results suggest that job type is associated with the prevalence of health and comfort complaints of office employees, with health more strongly associated than comfort.

Tables 4 and 5 give the prevalence of health symptoms and environmental dissatisfaction for each job type. These data show that while clerical workers have the highest overall health and comfort complaints, they have the lowest difference in complaints between sexes. Clerical workers showed no sex differences between the prevalence of 11 health symptoms and 11 environmental perception indicators. If the health and comfort of only females is considered, management and clerical workers report the highest prevalence of health symptoms and are the most dissatisfied with their work environment. Male management office workers, however, have the lowest prevalence of health symptoms and are the least dissatisfied with their work environment. Therefore, the observed sex differences between office workers appear to be mainly attributed to management.

In conclusion, there are sex-related differences in the prevalence of reported health and comfort indices in the office environment of buildings in which occupants complained of poor air quality. Investigations of health and comfort complaints should control for the sex distribution of office workers. Because female office workers experience more health symptoms and are more dissatisfied with their work environment, the sex distribution of the study population may act as a confounding variable even though the environments may be similar. Buildings with a higher proportion of female employees will appear to have more indoor environmental problems than buildings with a higher proportion of male employees.

The existence of sex differences between office workers after controlling for age and job type may be explained by a number of factors. (1) There may be differences in job type that are not examined by using job title. There is substantial evidence in the occupational stress literature that males and females tend to have different job characteristics in offices and that job characteristics are associated with health symptom and comfort reporting. (2) There may be true sex differences in the prevalence of health symptoms and environmental dissatisfaction of office workers. (3) Females may just report health symptoms and environmental dissatisfaction more than males. (4) There may be additional confounding factors, such as stress, that may influence the reported prevalence of health and comfort complaints of office workers.

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APPENDIX

The health symptom and environmental perception questions office workers were asked to respond to:

In your primary work area (that in which you spend the most time), how often did each of the following conditions occur in the last six months? (Answers were restricted to "never," "rarely," "sometimes," or "always.")

Too little air movement
Too much air movement
Just the right air movement

Air too dry
Air too moist
Humidity just right

Temperature too hot
Temperature too cold
Temperature just right

Lighting too bright
Lighting too dim
Too much glare on work surface
Lighting just right

Too noisy
Too quiet
Noise level just right

Air too smoky
Air too stuffy
Unpleasant odors in the air

Have you experienced any of the symptoms listed below while at work in this building in the last six months? (Answers were restricted to "never," "rarely," "sometimes," or "always.")

Headache
Fever
Cold/Flu symptoms
Nausea
Dizziness
Respiratory problems (breathlessness, wheezing)
Chest pain or tightness

Eye irritation
Sore or irritated throat
Nose irritation (itching or running)
Skin dryness, rash or itching

Muscular aches in arms, hands or wrists
Backache
Nechache

Depression
Tension or nervousness
Difficulty concentrating

Fatigue
Weakness
Sleepiness
Trouble focusing eyes
Cold extremities (feet, hands, etc.)

INDOOR AIR QUALITY DIAGNOSTIC PROCEDURES FOR SICK AND HEALTHY BUILDINGS

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ABSTRACT

With respect to environmental quality, two populations of existing buildings are apparent—those with known problems (i.e., problem buildings) and those with nonexistent problems (i.e., healthy buildings). A new discipline, known as building diagnostics, may be employed to identify and recommend solutions for problem buildings and to provide reasonable assurance that healthy buildings are not being compromised. However, the diagnostics procedures needed to address these two populations are somewhat different and present a dilemma. The accuracy of building diagnostics procedures can be evaluated by how well an actual event and the diagnosis (i.e., measurement or prediction and the occurrence of an event) agree. Two ways exist in which an actual event and the diagnosis can agree (i.e., two kinds of correct outcomes): "true-positive" and "true-negative." Similarly, there are two ways in which the event and the diagnosis can disagree (i.e., two kinds of errors): called "false-positive" and "false-negative." Building diagnostics performed for problem buildings seek to maximize the "true-positive" outcome (i.e., correctly diagnose an event) and minimize the "false-negative" outcome (i.e., fail to diagnose an event). Conversely, diagnostics performed for "buildings without known problems" (i.e., either healthy buildings or problem buildings) seek to maximize the "true-negative" outcome and minimize the "false-positive" or the "false-negative" outcome dependent on the relative risks incurred. A dilemma exists in using building diagnostics for this latter building population: Is it better to use diagnostics procedures which err toward the "false-positive" or the "false-negative" outcome?

In this paper, these two building populations are characterized, the basic concepts of building diagnostics are discussed, and the diagnostic procedures for problem buildings and buildings without known problems, respectively, are presented. Criteria used for evaluation and selection of instrumentation required for diagnostics to achieve the desired objectives are also discussed.

INTRODUCTION

Two populations of existing buildings are apparent when indoor environments are evaluated: those with known problems (i.e., problem buildings) and those without problems (i.e., healthy buildings). Based on a random survey in 1985 of 600 office workers in the U.S., it has been hypothesized that 20% of office workers (i.e., 20% of buildings) have problems which are manifested as symptoms associated with sick building syndrome (Woods et al. 1987a). Thus, in the complementary 80% of the U.S. building stock, these problems are either nonexistent (i.e., healthy buildings) or not known to exist.

A new discipline, known as building diagnostics, may be employed to identify and recommend solutions for problem buildings and to provide assurance that healthy buildings are not being compromised. Building diagnostics is described as ". . . a process in which a skilled expert draws on available knowledge, techniques, and instruments in order to predict a building's likely performance over a period of time" (Building Research Board 1985). Building diagnostics consists of four essential steps: 1) knowledge of what to measure, 2) availability of appropriate instrumentation, 3) expertise in interpreting results of measurements, and 4) capability of predicting building performance. From these steps, recommendations should follow that can improve system performance. As a derivative of building diagnostics, the two protocols (i.e., problem buildings and buildings without known problems) introduced in this paper are based on these four steps.

Building diagnostic procedures provide a mechanism to characterize a building in terms of three sets of parameters: 1) the type and location of sources of contaminants, 2) the four building elements that comprise a building system (i.e., structure, envelope, interior spaces, and services), and 3) performance characteristics during the life of the building.

The overall objective of this paper is to discuss how a common approach to building diagnostics can be used either to identify and evaluate causes of problem buildings or to provide reasonable assurance that design and operation of healthy buildings (including buildings without known problems) meet acceptable criteria. Specifically, this paper characterizes these two populations of buildings, describes

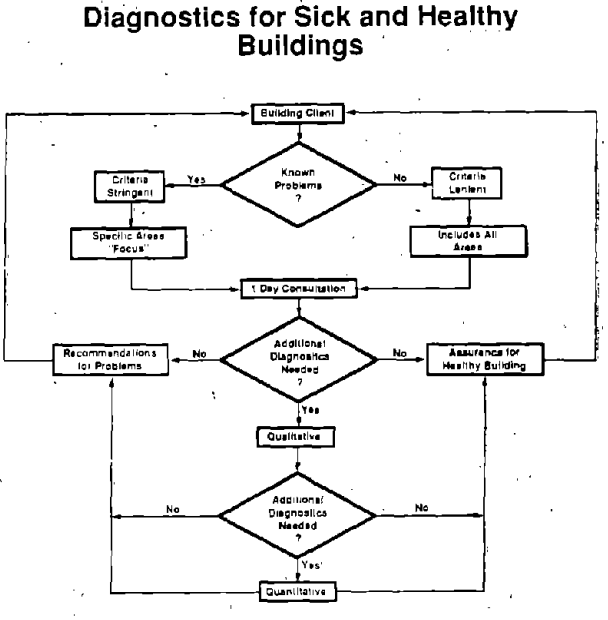

Figure 1 Two populations of non-industrial buildings for evaluation of environmental acceptability

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procedures for establishing evaluation criteria for diagnosing them, and highlights the similarities and differences in the respective diagnostic protocols.

CHARACTERIZATION OF BUILDING POPULATIONS

Problem Buildings

Problem buildings generally can be classified either as having occupants who are experiencing symptoms which are characterized as sick building syndrome (SBS), building-related illness (BRI), or both (Figure 1) (Woods 1988). When the complaints of a set of symptoms, including headaches, eye irritation, sore throat, fatigue, dizziness, drowsiness, and nausea, persist at frequencies significantly above 20% among occupants for periods of longer than two weeks, when the sources of complaints are not obvious, and when occupants usually obtain relief outside of the building, the building is considered to manifest SBS (Building Research Board 1987). The symptoms associated with SBS are actually related to responses of "acute discomfort" rather than frank illness (e.g., fever, infection, tissue deterioration). If symptoms of frank illness are present, the condition is often classified as BRI. Examples of this latter condition are occurrences of some nosocomial infections in hospitals (i.e., most nosocomial infections result from person-to-person transmission, rather than airborne transmission), humidifier fever, and Legionellosis.

An important difference between situations classified as SBS or BRI is that the etiology of SBS (e.g., a specific chemical contaminant) may not be necessary, as complaints are often resolved by increasing system ventilation, by discussions with the occupants, and by improved system maintenance. On the other hand, the etiology of a BRI incident usually must be determined before a solution can be implemented. In some instances, complaints registered by occupants do not exactly meet the symptoms that can be characterized as either SBS or BRI (e.g., complaints of environmental tobacco smoke). Complaints in these buildings can be characterized as "discomfort" rather than SBS or BRI.

When diagnosis of SBS or BRI reveals methods of control that can mitigate the problems, the building is then described as a "problem building" and engineering solutions are usually employed.

Buildings without Known Problems

Healthy buildings should have an absence of problems when evaluated by a building diagnosis. From a practical perspective, it is recognized that an occupied facility cannot exist without some problems. It is therefore suggested that a healthy building be characterized by three sets of criteria: human responses (e.g., no known clinical signs of BRI, and the frequency of reported SBS symptoms and discomfort complaints should be significantly below 20%); system performance (e.g., compliance with environmental criteria, uncontaminated air distribution ductwork and mechanical equipment, ease of maintenance, and proper balance of exhaust and makeup air); and service factors (e.g., periodic inspections of HVAC systems, accurate records of occupants' complaints, scheduled filter changing, and HVAC system control calibration) (Woods 1988). If problems are identified, then the building is no longer characterized as a healthy building and diagnostic procedures used in problem buildings are performed.

DIAGNOSTIC STRATEGIES

The accuracy of building diagnostics procedures can be evaluated by how well an actual event and the diagnosis (i.e., measurement or prediction of the occurrence of an event) agree. Two ways (Figure 2) exist in which an actual event and the diagnosis can agree; that is, two kinds of correct outcomes, called "true-positive" and "true-negative" (Swets 1988). Similarly, there are two ways in which the event and the diagnosis can disagree; that is, two kinds of errors, called "false-positive" and "false-negative."

Building diagnostics performed for problem buildings seek to maximize the "true-positive" outcome (i.e., correctly diagnose an event) and minimize the "false-negative" outcome (i.e., fail to diagnose an event). In these buildings, problems are assumed to exist, thus diagnostic procedures are used which "focus" the evaluation on those parameters that directly impact the known problem areas and exclude other areas (i.e., diagnosis by exclusion). This diagnostic approach is different from the approach taken by investigators who attempt to utilize conventional industrial hygiene hazard evaluation techniques in non-industrial buildings. More stringent environmental criteria are established and instrumentation for obtaining data must be appropriately sensitive. For these cases, some "false-positive" outcomes are expected (Swets 1988).

Conversely, diagnostics performed for healthy buildings (including buildings without known problems) seek to maximize the "true-negative" outcome and minimize the "false-positive" outcome or the "false-negative," dependent on the relative risks incurred. In these buildings, diagnosis by inclusion is used. Thus, the "scope" of the diagnostic procedures is large (i.e., encompassing the entire building) and not "focused" on a known problem area (i.e., a specific area in the building). If it is believed more desirable to minimize the "false-positive" outcome, relatively lenient performance criteria are established and instrumentation for obtaining data may be less sensitive. If it is judged more desirable to minimize the "false-negative" outcome, more restrictive performance criteria and more sensitive sampling and analysis methods, such as those used in problem buildings, will be used.

A dilemma exists in using building diagnostics for buildings without known problems: Is it better to use diagnostics procedures which err toward the "false-positive" or the

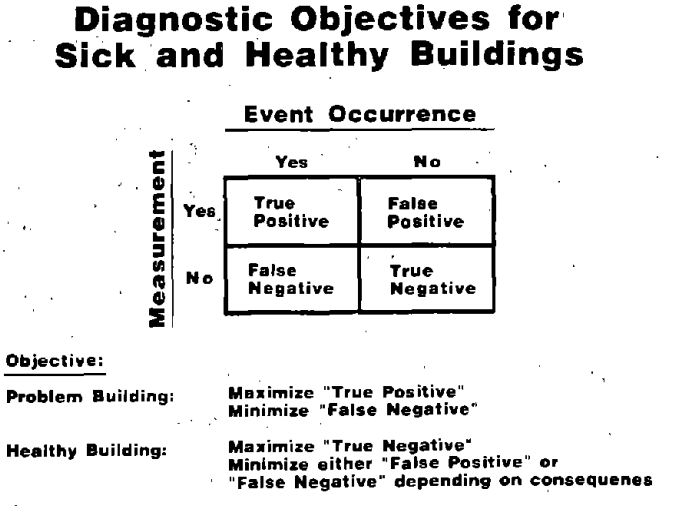

Figure 2 Diagnostic objectives for problem buildings and buildings without known problems

"false-negative" outcome? The answer will depend on the benefits ascribed to the correct outcomes and the costs ascribed to the incorrect outcomes. For example, predicting the occurrence of an excessive concentration of bacteria that does not occur (i.e., a false-positive) is regarded as having a cost that is small relative to the cost of failing to predict an occurrence that does occur (i.e., false-negative), so the criteria adopted for a positive diagnosis are on the stringent side. Conversely, lenient criteria are established when the cost of a false-positive outcome is disproportionately high. Take, for example, the case of an office where no SBS or BRI symptoms have been reported. If environmental monitoring is done in this office for volatile organic compounds (VOC) using sensitive techniques, and the results indicate concentrations to be in excess of stringent performance criteria, it may be difficult to justify the high cost of additional ventilation to reduce VOC concentrations in this office area considering the uncertain risk of continuing exposure at the concentrations measured.

The basic principles of building diagnostics provide guidance in resolving this dilemma. Clearly, in both classifications of buildings, the investigator has two choices: 1) take rigorous objective measurements for all possible contaminants; or 2) as a first step, characterize the building as a "system" comprised of building elements (i.e., structure, envelope, interior spaces, and services), formulate a preliminary hypothesis (i.e., evaluate the relationships between contaminant sources, symptoms, and building systems), identify preliminary recommendations, and perform additional diagnostics as necessary. Obviously, the first option is neither technically nor economically feasible. The second option is not only technically and economically feasible, but is consistent with the basic philosophy of building diagnostics (i.e., knowledge of what to measure, availability of appropriate instrumentation, expertise in interpreting results of measurements, and capability of predicting building performance).

In both populations of buildings, the first step in building diagnostics is to determine evaluation criteria. Next, the building is characterized as a complete "system." In problem buildings, only those relationships that impact the problem area are evaluated (i.e., a limited scope of the problem). In buildings without known problems, the interaction of building systems in the entire building is characterized until all existing or potential problem areas are identified and evaluated for compliance with criteria. Once problem areas are identified, diagnostic procedures for both building populations are similar. Next, the evaluation focuses on specific possible contaminant sources, symptoms, and system interaction in the problem area(s) by formulating a "preliminary hypothesis." Finally, the evaluation validates or modifies the preliminary hypothesis by obtaining only the objective and subjective data which are necessary to validate the hypothesis.

Diagnostic procedures performed in the initial stage of building evaluation provide the mechanism by which a "trained" diagnostician can "qualitatively" (i.e., without measuring data) determine, with reasonable confidence, the acceptability of the indoor environment and evaluate the need for additional diagnostics. Philosophically, the same diagnostics procedures can be used in both problem buildings and in buildings without known problems. The primary difference between the two populations of buildings is that the "scope" of the initial step in the evaluation is larger in buildings without known problems than in problem buildings. However, more rigorous diagnostic procedures (i.e., establishing additional criteria and obtaining objective and subjective data) are not employed until an initial qualitative evaluation is performed and a need for quantitative diagnostics is identified.

OUTLINE OF PROTOCOLS

As a derivative of building diagnostics, the two protocols (i.e., problem buildings and buildings without known problems) introduced in this paper are based on the four steps of building diagnostics (Figure 3). These protocols utilize both engineering principles for system analysis and scientific principles for measurements of contaminant concentrations and for human responses (Woods et al. 1987b). They take advantage of the understanding required to evaluate compliance with both prescriptive and performance criteria for acceptable indoor air quality.

A fundamental aspect of both protocols is that knowledge is required of the relationships that exist among the building, its systems, and its occupants. For problem buildings and buildings without known problems, diagnostics are performed by a three-phase procedure.

Problem Buildings

Phase 1: Consultation. The objective of this phase is to focus diagnostic procedures on the problem area(s). In this phase, the building is characterized in four categories: 1) structure, 2) envelope, 3) occupied spaces, and 4) building services. The structure and envelope (e.g., foundation, load-carrying elements, exterior walls, windows, doors, roof, etc.) are inspected. Available plans and construction documents are reviewed to characterize heat transfer rates through the envelope and routes of contaminant transport from outdoor sources. This characterization includes identification of potential contamination of makeup air intakes; integrity of vapor barriers in walls and roofs; and deficiencies in the foundation, structure, and envelope which allow transport of moisture and other contaminants into the building. The scope of the investigation and its objectives are defined, a preliminary hypothesis may be formulated, and preliminary recommendations may be presented to the client. "Measurements" during this phase consist of "professional observations" by the investigators. A preliminary determination of what subsequent measurements may be required to better characterize the building is also made during this phase. The scope of the problem may be one specific area of the building or the entire building.

Phase 2: Qualitative Diagnostics. If this phase is needed to test the preliminary hypothesis or to validate the preliminary recommendations, it will be accomplished primarily through engineering analysis techniques. In this phase, additional performance criteria for the various functional areas of the building will be defined. If health problems are not

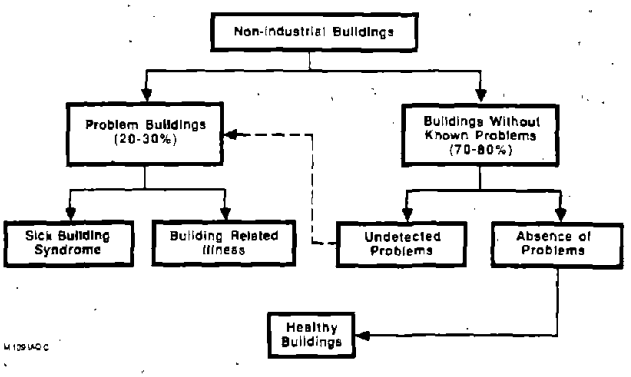

Figure 3 Diagnostics flow chart

suspected, analysis of system performance will be initiated, and measurements will be limited to those required to evaluate the system servicing the problem area(s). Thermal and contaminant loads that are generated within these areas are estimated for subsequent analysis of system performance. The services are characterized by inspection, objective measurements, and review of plans and construction documents. The capacities of the HVAC systems are evaluated in terms of their capabilities of meeting the thermal and contaminant loads imposed on them. Control strategies and systems are evaluated to determine their effectiveness in providing the required energy-efficient and cost-effective environmental conditions within the occupied spaces. However, if health problems are suspected (BRI), immediate medical attention will be recommended for the affected occupants. Based on results of the medical evaluation, specific pollutants may be identified, and airborne and bulk samples of suspected pollutants will be obtained, as described in Phase 3.

An important aspect of this phase is that measured data are not always essential to identify and solve problems.

Phase 3: Quantitative Diagnostics. If further investigation is needed to test the hypothesis or to validate the recommendations, quantitative measures of airborne contaminant concentrations, bulk samples, and other environmental parameters will be acquired through a systematic format. Also, a thorough quality assurance/quality control program will be implemented. In this phase, both objective measurements of the physical environment and subjective responses of the occupants are obtained. To characterize the interior spaces, a systematic, efficient procedure is followed to identify "areas of maximum and minimum potential exposures" within each functional category of the building. Objective measures of thermal, acoustic, lighting, and air quality may be obtained in these areas and in the outdoor air by use of instrumentation specifically adapted and standardized for this purpose. Simultaneously, subjective measures of occupant responses (i.e., perceived responses, symptoms, and demographics) may be obtained in these areas by use of questionnaires developed and standardized for this purpose.

Buildings without Known Problems

The diagnostics procedures for buildings without known problems are similar to those used in problem buildings, with two exceptions. First, the scope of the procedures used in the first phase (i.e., consultation phase) is greater since the entire building must be characterized and not just problem areas. Second, the procedures provide the building owner or occupants with a choice of two "levels" of assurance (i.e., confidence level) that problems do not exist: 1) a "reasonable" level of confidence based on qualitative evaluation of the building characteristics (i.e., qualitative assurance), or 2) a greater level of confidence based on the results of obtaining objective data (i.e., quantitative assurance). In either procedure, criteria are first established for the three components that characterize a healthy building: 1) the overall indoor environment (i.e., thermal, lighting, acoustic, and air quality), 2) the system performance (i.e., ventilation efficiency, adequate outdoor air, proper air balance and distribution, supply and return air ductwork that is not conducive to contaminant accumulation, and ease of maintenance), and 3) the service factors (i.e., periodic inspections of all components comprising the HVAC system, scheduled filter changing or cleaning, scheduled control calibration, scheduled air and hydronic balancing of the system, structured preventive maintenance program, and proper records to document occupant complaints and symptoms. If the qualitative assurance procedure is chosen, compliance with criteria is based on observing the general conditions (i.e., characterization) of the facility that exist during the time that the evaluation is performed (i.e., professional judgment). No objective or subjective measurements are obtained. This evaluation procedure results in a "reasonable" level of confidence that the environmental quality, system performance, and service factors comply with selected criteria; however, no record of actual indoor air quality data is provided. If the quantitative assurance procedure is selected, areas with maximum potential for indoor air quality problems are selected. Objective and subjective data are obtained in these areas and evaluated for compliance with criteria. The objective of either evaluation procedure is to identify any existing or potential problem areas with reasonable confidence and develop preliminary recommendations as necessary. If no problems are identified, the building can be considered "healthy."

CONCLUSIONS

Two primary conclusions can be derived from the concepts of building diagnostics presented here:

1. The same principles of building diagnostics developed for investigating problem buildings are also useful for ensuring the performance of healthy buildings; however,
2. The scope of the investigation and the criteria used for compliance evaluation differ for these two populations of buildings (i.e., the investigation of a healthy building is more inclusive, but the criteria may not be as stringent).

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OBJECTIVE MEASURES AND PERCEIVED RESPONSES OF AIR QUALITY IN TWO HOSPITALS

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ABSTRACT

Investigations of indoor air quality in healthy or problem buildings may produce objective and subjective data (occupant perceptions) which do not correlate and which are difficult to interpret. In this paper we investigate the relationship between objective and subjective measures in six matched sites of two hospitals, one hospital without known "sick building syndrome" (SBS) complaints, and a second hospital with known SBS complaints. Objective data were obtained for thermal, lighting, acoustic, and air quality parameters by direct-reading instruments or, in the case of selected volatile organic compounds, by collection on porous polymer media beds with subsequent GC/MS analysis. Subjective data are human responses to the environment, which were recorded via occupant questionnaire. All objective results met acceptable environmental and health evaluation criteria with the exception of dew point temperature in the hospital with SBS complaints. Perceptions of discomfort were reported by employees of both hospitals but these responses were noted more often in the hospital with known SBS complaints. Perceived responses of occupants are frequently more sensitive indicators of indoor air quality problems than are the objective measures conventionally relied upon for exposure evaluation. Therefore, effective building diagnostic protocols should incorporate observations, investigation of management strategies, measurement of environmental variables, and perceived responses to the environmental conditions as a basis for system evaluation, predictions of future system performance, and recommendations for improvements.

INTRODUCTION

Human responses to the indoor environment are affected by four primary types of environmental stressors: thermal, acoustic, illumination, and air quality. When these stressors are within acceptable limits, they may be perceived to be pleasant or comfortable. Buildings in which these responses are achieved may be characterized as "healthy buildings" (Woods 1988). However, if these stressors exceed acceptable limits, then discomfort, symptoms associated with "sick building syndrome" (SBS), or clinical signs indicative of "building-related illness" (BRI) are likely to result. Sick building syndrome is characterized by symptoms of acute discomfort (e.g., headache, dizziness, eye irritation, fatigue, sore throat, or nausea) which persist for more than two weeks at frequencies significantly greater than 20%; the cause(s) of these symptoms are not recognizable; a substantial percentage of occupants report almost immediate relief upon exiting the building. Building-related illness is characterized by symptoms of frank illness (e.g., fever, muscle ache, and tightening of the chest) which usually persist after leaving the building (Building Research Board 1985).

The goals of indoor air quality evaluations are to identify and control environmental stressors so that health risks are minimized and occupants perceive a healthful and comfortable environment. Objective and subjective measures can be utilized to evaluate the environment, particularly the indoor air quality. However, in some cases, complaints of symptoms or discomfort in nonindustrial facilities are the only manifestation of indoor environmental problems. The importance and difficulty in matching objective data with occupant perceptions have been recognized by several investigators, even in controlled studies (Bergland et al. 1982; Burge et al. 1987; Carlton-Foss 1984; Fanger 1988; Hodgson 1986; Kreiss et al. 1984; Building Research Board 1987; National Research Council 1981; Spengler 1983; Skov 1987). Even greater difficulty in diagnostic investigations may be caused by: 1) impracticality of using ideal instrument(s) or method(s); 2) confounding of human responses by other stressors (i.e., psychosocial conditions including labor-management relations and socio-economic status; or confounding factors, such as age, sex, smoking status, ethnicity, or pre-existing medical conditions); 3) instruments and methods used to obtain objective measures of environmental conditions are often less sensitive than the subjective instruments and methods used to measure occupant perceptions; and 4) impracticality of acquiring sufficient data for conventional statistical analysis.

This paper illustrates the point that evaluation of buildings, whether they are associated with SBS or not, may produce objective and subjective data which are not well correlated and which are difficult to interpret. It is important to note that this paper is based on two field investigations which, by nature, are limited in scope, rather than controlled research studies.

PROCEDURES

Site Selection

To investigate the relationship between objective and subjective measures, two buildings have been selected with similar functions and populations and which are located in the same region within the United States. Hospitals have been chosen because they offer a wide variety of functional categories—some unique—but many that are also similar in function to commercial, administrative, or institutional buildings. For example, administrative functions within a hospital are similar to the administrative function in an office building and the laboratory suite of the hospital is comparable to a laboratory in an educational or institutional setting. These comparable functional categories between hospitals and other buildings are possible because of similarities between activities, populations, and environmental conditions. Thus, the findings within hospitals are apt to represent buildings at large.

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The two hospitals are located in the metropolitan area of a large city in the northeastern United States. Hospital A was used to test indoor air quality procedures and equipment and had no known occupant complaints or symptoms related to indoor air quality. Hospital B was one in which a substantial number of occupants reported thermal discomfort problems and symptoms associated with sick building syndrome and, possibly, building-related illness.

Hospital A is located in a suburban area and contains approximately 270 beds in a total floor area of approximately 292,000 ft^2. The hospital was built over three construction periods during the mid-1940s, late 1960s, and early 1970s. The two older sections of the hospital had undergone extensive renovation. Heating, air-conditioning, and ventilation in Hospital A were provided by 24 supply and 39 exhaust systems located in 10 mechanical equipment rooms throughout the hospital, in addition to perimeter heating systems in the nursing areas.

Hospital B is located in the core of the metropolitan area and contains about 430 beds in a total floor area of approximately 387,000 ft^2. Most of Hospital B was built in the early 1960s, however, an addition was completed in the mid-1980s. Most of the hospital had not undergone substantial renovation. Heating, air-conditioning, and ventilation were provided by 10 air-handling systems in addition to perimeter heating systems in the nursing area.

A notable difference between the two hospitals was the relative importance placed on the engineering departments. In Hospital A, the director of facilities management reported to the hospital administrator. The director was a professional engineer and was active in professional organizations. The engineering staff was well-trained and capable of all aspects of facilities operation and maintenance. An excellent set of as-built drawings was maintained. The engineering department had excellent relations with the medical and administrative staffs and had the authority to execute its responsibilities. In Hospital B, the hospital engineer was two levels of management removed from the hospital administrator. Although the hospital engineer had formal engineering education, he was not registered nor was he active in professional organizations. The skeleton staff was not trained in all aspects of facilities operation or maintenance. As-built drawings did not exist. The engineering department was not respected by the medical or administrative staffs and little authority was given to the department to execute its responsibilities.

Measurements

Objective and subjective environmental data were obtained at both hospitals. These data were collected at several different sites within the various functional areas of each hospital. Representative sample sites at each hospital were selected with the use of a "standardized site selection procedure" developed for diagnosis of indoor air quality problems. This selection process was accomplished through the visual evaluation of each room in order to assign the room scores for three indices: 1) contaminant sources, 2) susceptibility of the occupants, and 3) ventilation effectiveness. Generally, the room having the most undesirable combination of these three characteristics was selected as the sample site for the functional area that it represented (i.e., "maximum potential exposure site"). Data acquisition periods were typically 90 minutes at each site.

Comparison of the sample sites of the two hospitals identified six pairs of sites which emerged as having sufficient similarities to allow comparison of the objective and subjective data obtained at each of these sites. These six pairs of sites represent six different functional categories. Table 1 lists the six pairs of sites discussed in this paper.

TABLE 1

Sites Selected for Comparison of Objective and Subjective Measures.

Site No.	Functional Category	Hospital A	Hospital B
1.	Administrative Facilities	Medical Records	Medical Records
2.	Diagnostic Treatment Facilities	Laboratory Suite — Chemistry Lab	Laboratory Suite — Chemistry Lab
3.	Nursing Facilities	Patient Room — Oncology	Patient Room — Oncology
4.	Surgical Facilities	Cystoscopic Room	Operating Room
5.	Central Sterilizing & Supply	Sterilization Room including Wraproom	Sterilization Room including Wraproom
6.	Obstetrical Facilities	OB Recovery Room	OB Recovery Room

Objective Measures

Objective data were obtained for thermal, lighting, acoustic, and air quality parameters. Thermal measures include dry-bulb temperature, dew point temperature, plane radiant temperature, and air movement, which were measured by a platinum resistance element, chilled mirror mechanism, radiant heat exchanger, and an anemometer, respectively. Lighting measures in terms of illuminance were obtained by a cosine-corrected silicon photocell. Acoustic measures, specifically sound pressure levels, were obtained through the use of a sound level meter with an A-weighting.

A number of air quality components were measured, including particulate size distribution, particulate mass, microbiological aerosols, oxides of nitrogen, carbon dioxide, various volatile organic compounds, and ventilation rates. Particulate counts by size distribution ($\geq$ 0.3 μm diameter) were obtained by an instrument utilizing a light-scattering mechanism; and total mass of particulates in the size range of 0.1 to 20 μm was also measured by a light-scattering instrument. Microbiological aerosols were collected via a multi-orifice, single-stage impactor onto 100 mm agar plates with media selective for the growth of mesophilic fungi according to the American Conference of Governmental Industrial Hygienists' guidelines for sampling and assessing bioaerosols (Burge et al. 1987). The oxides of nitrogen were quantified using an instrument that utilized chemiluminescence. Carbon dioxide (CO_2) data were obtained with an infrared analyzer.

The methods of measuring selected volatile organic compounds (VOC) varied between the two hospitals. One of the objectives in the study of Hospital A was to develop a diagnostics protocol and to select air quality indicators and methods of measuring air quality components. The instrument selected for use in Hospital A for measuring air quality constituents utilized fourier transform infrared spectrophotometry. Interferences from atmospheric water and ambient carbon dioxide masked the low VOC concentrations, so a more selective method of VOC analysis was chosen for Hospital B. In Hospital B, VOC were collected on porous poly-

TABLE 2

Comparison of Thermal Data in Two Hospitals.

Functional Area	Site	Hospital A (n = 90) Dry-Bulb Temp. (Mean ± SD°C)	Hospital A (n = 90) Dew Point Temp. (Mean ± SD°C)	Hospital B Dry-Bulb Temp. (Mean ± SD°C)	Hospital B Dew Point Temp. (Mean ± SD°C)	n
Medical Records	1	24.2 ± 0.1	13.8 ± 0.1	25.9 ± 0.6	1.1 ± 0.2	n = 90
Chemistry Lab	2	24.4 ± 0.6	12.0 ± 0.1	24.4 ± 0.2	2.1 ± 0.6	n = 88
Patient Room	3	26.8 ± 0.3	16.2 ± 0.2	26.6 ± 0.4	−2.7 ± 0.3	n = 87
Surgical Facilities	4	19.6 ± 0.2	9.6 ± 0.3	19.1 ± 0.2	−1.8 ± 0.3	n = 117
Central Sterilizing and Supply	5	24.5 ± 0.3	17.2 ± 0.2	27.4 ± 0.6	1.9 ± 4.7	n = 90
OB Recovery	6	26.2 ± 0.1	17.0 ± 0.2	22.8 ± 0.1	−4.4 ± 0.5	n = 90
Outdoor Site		27.0 ± 3 (n = 17)	25.0 ± 3 (n = 17)	9.9 ± 1.5	−5.8 ± 0.8	n = 60

TABLE 3

Comparison of Aerosols in Two Hospitals.

Functional Area	Site	Particulates (Mean + S.D.) Count (# In Millions of > 0.3 μm/m³) A	Particulates (Mean + S.D.) Count (# In Millions of > 0.3 μm/m³) B	Microbial Concentration (n = 1) (CFU/m³) A	Microbial Concentration (n = 1) (CFU/m³) B
Medical Records	1	30.0 ± 3.9 (n = 90)	10.6 ± 2.7 (n = 87)	37	53
Chemistry Lab	2	18.6 ± 5.9 (n = 90)	12.7 ± 4.1 (n = 90)	53	53
Patient Room — Oncology	3	173.5 ± 16.0 (n = 90)	10.4 ± 0.5 (n = 90)	27	106
Cystoscopic/O.R.	4	4.3 ± 0.2 (n = 90)	4.8 ± 0.9 (n = 120)	25	9
Central Sterilizing and Supply	5	68.2 ± 39.8 (n = 90)	63.4 ± 7.8 (n = 90)	42	82
OB Recovery	6	65.5 ± 7.6 (n = 90)	164.4 ± 2.3 (n = 89)	19	94
Outdoor Site		96.7 ± 14.6 (n = 76)	20.8 ± 1.1 (n = 59)	NA	88–212 (n = 6)

NA = Not Available

mer adsorbent beds which were thermally desorbed, cryofocused, and analyzed via capillary gas chromatography/mass spectrometry. Differences in VOC methods between Hospital A and Hospital B made it difficult to compare data between the two hospitals.

Ventilation rates were determined by at least one of three methods: 1) tracer gas analysis, 2) CO_2 analysis, and 3) airflow measurement. Tracer gas analysis consisted of releasing sulfur hexafluoride (SF_6) into the occupied space, measuring the tracer gas decay with an infrared analyzer or electron capture gas chromatograph, and calculating the room air exchange rates (ach) and occupant-normalized ventilation rates (L/s per person). CO_2 analysis consisted of measuring the difference between indoor and outdoor CO_2 concentrations with an infrared analyzer, determining the percent of outdoor air provided by the system by airflow measurements, and by calculating the air exchange and ventilation rates from estimates of the CO_2 generation rates by the occupants. Airflow measurements consisted of volumetric flow measurements at supply diffusers with "flow hoods" and volumetrics, and pitot transverses of duct sections.

Subjective Measures

Occupant environmental questionnaires were completed by sampling hospital staff; patients were not selected for the subjective evaluation procedure. The questionnaires, shown in Figure 1, were used to record subjective responses to the environmental stresses imposed by thermal, air quality, acoustic, and lighting factors. The validity of these questionnaires for determination of environmental acceptability has been previously reported (Rohles et al. 1987, 1989). The primary purpose for using these forms in these two hospitals was to obtain perceptions of the environmental quality which may be correlated to the objective measures.

The occupant questionnaire provided information from staff in the selected functional areas regarding individual perceptions of the indoor environment during the period that objective measures were also being acquired. Questionnaires were administered one to three times during objective data acquisition periods. Twelve components of the indoor environment were rated on a six-point scale, with one being very unacceptable and six being very acceptable. Individuals were also asked to rate the overall air quality of their work envi-

Date _____ Time _____ AM
_____ PM

ENVIRONMENTAL QUESTIONNAIRE

Listed below are 12 items related to the environment of the area in which you work. In front of each item, enter the number from the following acceptability scale that best describes the acceptability of your work area at this time.

6 = very acceptable
5 = acceptable
4 = somewhat acceptable
3 = somewhat unacceptable
2 = unacceptable
1 = very unacceptable

_____ temperature

_____ humidity

_____ air movement

_____ odor (or smell)

_____ amount of dust

_____ amount of tobacco smoke

_____ loudness of the sounds

_____ pitch (or frequency or tone) of the sounds

_____ number of noisy distractions

_____ brightness of the lighting

_____ glare

_____ shadows

_____ OVERALL QUALITY

Please answer the following questions by filling in the blank or circling the correct response:

What is your age <20 ____; 20-29 ____; 30-39 ____; 40-49 ____;
50-59 ____; 60-69 ____' >70 ____

What is your gender? Male Female

Are you currently a tobacco smoker? YES NO

Have you smoked at your workstation during the past hour?
YES NO

Please circle any of the following symptoms that you may have AT THIS POINT.

HEADACHE	UNEXPLAINED MEMORY LOSS
BACKACHE	STIFF ARM
DROWSINESS	NOISE IRRITATION
HAND CRAMPS	ITCHY SKIN OR RASH
EYE IRRITATION	NECK PAIN
DRY MUCOUS MEMBRANES	MENTAL FATIGUE
SORE THROAT	LEG CRAMPS
ITCHY FOOT	DRY SKIN

Other current symptoms that may be related to your work environment: _____

_____

_____

Figure 1 Environmental questionnaire used for subjective measures (Rohles et al. 1987, 1989; Woods et al. 1987)

TABLE 4

Comparisons of Selected Gases and Vapors in Two Hospitals.

Functional Area	Site	Carbon Dioxide (Mean + S.D.) (ppm) A	Carbon Dioxide (Mean + S.D.) (ppm) B	Volatile Organic Compounds (ug/m³) (n = 1) A	B Dichloroethane	B Toluene	B Limonene
Medical Records	1	639 ± 38 (n = 90)	533 ± 18 (n = 90)	NA	442	7	2
Chemistry Lab	2	422 ± 19 (n = 88)	NA	NA	147	14	2
Patient Room — Oncology	3	503 ± 45 (n = 87)	463 ± 22 (n = 89)	NA	211	134	56
Cystoscopic/OR	4	319 ± 31 (n = 85)	387 ± 9 (n = 120)	NA	101	162	2
Central Sterilizing and Supply	5	373 ± 11 (n = 87)	449 ± 34 (n = 89)	NA	584	397	2
OB Recovery	6	373 ± 25 (n = 87)	526 ± 51 (n = 92)	NA	303	87	4
Outdoor Site		290 ± 13 (n = 102)	298 ± 44 (n = 59)	NA	32	7	ND

NA = Not Available
ND = Non-Detectable

TABLE 5

Derived Occupant-Normalized Ventilation Rates in Two Hospitals.

Functional Area	Site	Occupancy Density (No. People/ 100m² Floor Area) A	Occupancy Density (No. People/ 100m² Floor Area) B	Occupant-Normalized Ventilation Rate (1/s Per Person) Reference Method A (Tracer Gas)	Reference Method B (Air Flow)	CO_2 Method A	CO_2 Method B
Medical Records	1	11	10	41	NA	21	24
Chemistry Lab	2	6	NA	NA	NA	58	NA
Patient Room — Oncology	3	14	15	43	NA	35	42
Cystoscopic/O.R.	4	14	12	133	69	106	80
Central Sterilizing and Supply	5	3	3	NA	NA	97	48
OB Recovery	6	6	8	100	NA	99	32

NA = Not Available

ronment. In addition, four personal questions were asked to obtain demographic information on age, sex, and smoking status. Occupants also were asked to select from a list of symptoms those which they were experiencing during the monitoring period. Of these symptoms, nine were intended to relate to characteristic complaints of sick building syndrome and seven were intended to be unrelated to air quality issues. Survey participants were also invited to write in other symptoms that were not on the list.

Quality Assurance/Quality Control

A quality assurance/quality control program was developed and implemented for the diagnostic procedures employed to study these hospitals. This program required the use of standard methods, qualified laboratories, stringent calibration practices, sample/data chain-of-custody procedures, and other practices to ensure reliable, accurate, and representative data.

RESULTS

Objective Results

The results of the thermal, lighting, acoustic, aerosol, gas, and vapor measures, and ventilation rates are shown in Tables 2 through 5.

Thermal. In Hospital A, the plane radiant temperature differences were no greater than 0.5°C and in Hospital B, the plane radiant temperature differences ranged between 0.5°C and 3.6°C in the selected areas. These differences were within acceptable limits (< 7.8°C) according to ASHRAE Standard 55-1981 (ASHRAE 1981a). Air speed measurements in Hospital A were less than 0.35 m/s at the selected sites and were less than 0.16 m/s in Hospital B. Metabolic rates and clo values (ASHRAE 1985) were normal for hospital staff and were not expected to directly influence differences in responses to the thermal conditions.

Table 2 lists thermal conditions in terms of dry-bulb and dew point temperatures in the six paired sites selected for

this comparison. Indoor dry-bulb temperatures were not substantially different between hospitals and were quite similar when compared by functional area. On the other hand, there were substantial differences in dew point temperatures between Hospital A and Hospital B. In general, dew points in Hospital A ranged from 9.6° to 17.2°C (i.e., 52% to 64% RH) and from -2.7° to 2.1°C (i.e., 14% to 23% RH) in Hospital B. Hospital A was evaluated in the summer and Hospital B was evaluated in the early spring. Humidity control was provided during the test period in Hospital A by the chilled water coils in the central air-conditioning units, but humidity control was not available during the test period in Hospital B since the steam humidifiers had been deactivated. The dew point temperatures in Hospital B, which had reported problems, were substantially lower than those in Hospital A, which did not have reported problems, and were also lower than ASHRAE 55-1981 guidelines (ASHRAE 1981a).

Acoustics and Illuminance. Both acoustic and illuminance conditions were within acceptable ranges for the hospital environment. Average sound pressure levels in Hospital A ranged from 57 ± 5 to 66 ± 4 dBA. Average sound pressure levels in Hospital B ranged from 54 ± 5 to 66 ± 6 dBA. Sound pressure levels did not vary greatly between areas within either hospital nor were there substantial differences when the paired sites were compared. Illuminance data were evaluated for each site at the two hospitals. Unfortunately, these data cannot be compared because data were not recorded from comparable work surfaces within each functional area.

Aerosols. Two types of aerosol data were acquired in the hospitals: particulate and microbial aerosols. Particulate data included particulate mass per m^3 of sampled air and number count of particulates greater than or equal to 0.3 μm diameter per m^3. Particulate mass in Hospital A ranged from 3 to 65 $\mu g/m^3$. Particulate mass in Hospital B ranged from 1 to 9 $\mu g/m^3$. Table 3 contains a list of particulate count by hospital and by paired site. Interestingly, the particulate concentrations of problem Hospital B were generally less than the particulate concentrations in non-problem Hospital A in four of the six sites.

Single samples of viable microbial concentrations (colony-forming units/m^3) are also presented in Table 3 for each site. The microbial population in each hospital was similar in taxa and concentration throughout each respective building. Furthermore, the population in Hospital B was also similar in taxa and concentration to the outdoor air concentration. Microbial aerosol problems were not apparent in either hospital, as substantial concentrations of pathogenic or opportunistic microorganisms or bioamplification sites were not detected. No substantial conclusions can be drawn by comparing interhospital microbial data because of the many confounding factors such as season, time of day, weather patterns, locale, etc.

Gases and Vapors. The results of gas and vapor sampling at the two hospitals are shown in Table 4. Carbon dioxide (CO_2) measurements in Hospital A ranged from approximately 319 ppm to 639 ppm and Hospital B concentrations ranged from about 387 ppm to 533 ppm. Both outdoor concentrations were similar at 290 and 298 ppm, respectively. CO_2 concentrations may be associated with the ventilation strategy serving the site. In Hospital A, Medical Records utilized recirculated air and the CO_2 levels were twice as high as outdoor levels and were generally higher than all other sites, which did not recirculate air. In Hospital B, this association is less distinct, as Medical Records and Central Sterilizing & Supply utilized recirculated air and had CO_2 concentrations only slightly higher or the same as the other sites without recirculated air. Obviously, source load and the degree of ventilation effectiveness in the nonrecirculating areas of the hospital influence the CO_2 concentration.

Selected volatile organic compounds for Hospital B are reported in Table 4 also. The three compounds listed were chosen because in Hospital B they were the three "most significant" concentrations of 21 VOC measured. These concentrations were higher than outdoor concentrations.

Ventilation Rates. The derived values of occupant-normalized ventilation rates (i.e., L/s person) are shown in Table 5, together with the occupant densities observed during the data acquisition periods. The occupancy densities for the functional areas in both hospitals were surprisingly similar. With the exception of the Medical Records area in Hospital A, the ventilation rates derived by the CO_2 method were within 20% of those derived by the reference (i.e., tracer gas or airflow) methods at four of the five sites where comparisons could be made. It is significant to note that all of the derived ventilation rates were 2 to 6 times higher than the minimum values required in ASHRAE Standard 62-1981 or proposed in 62-1981R (ASHRAE 1981b, 1981c). It is particularly important to note in Table 5 that the ventilation rates, derived from CO_2 data, were similar for three of the five sites compared in Hospitals A and B.

Subjective Results

The subjective results are data provided by employees who agreed to participate in the subjective evaluations. These results include a report of SBS symptoms and scoring—on a one to six scale—of the acceptability of various environmental parameters related to the building.

Symptoms. Table 6 contains a comparison of the number of SBS-associated symptoms which were reported by occupants within selected sites of Hospitals A and B. Generally, a building or occupied space is suspected of having an SBS problem if more than 20% of the occupants report two or more of these symptoms. Note that in Hospital A, which was considered the non-problem building, occupants in three sites reported an average of two symptoms.

Hospital B, with known SBS complaints, had higher average numbers of SBS symptoms—three out of six sites reported an average of more than two SBS symptoms.

Perceptions. The results of the perceived responses by employees in Hospital A and Hospital B are shown in Table 7. Perceptions of the environment for each of the six sites are shown for the thermal, air quality, acoustic, and lighting parameters. Note that the scores are reported as means of the six-point scale plus or minus the standard error for the replicates of the given sample size. The rating given each score is as follows: 1 = very unacceptable; 2 = unacceptable; 3 = somewhat unacceptable; 4 = somewhat acceptable; 5 = acceptable; and 6 = very acceptable.

There are substantial differences in occupant perceptions between Hospital A (non-problem) and Hospital B (problem). Generally, Hospital A reported a higher overall level of acceptability than Hospital B (i.e., three of five sites evaluated in Hospital A had an average overall score of 5, while only one of six in Hospital B had a score of 5). Hospital B consistently had the lowest scores of thermal and air quality perceptions, with the exception of the operating room. The chemistry labs, oncology patient rooms, and central sterilization areas had the largest reported differences for specific parameters between hospitals. It is probable that dissatisfac-

TABLE 6

Comparisons of the Number of SBS Symptoms Reported in Two Hospitals.

Functional Area	Site	Hospital A (Average Number of SBS Symptoms)	Hospital B Average Number of SBS Symptoms)
Medical Records	1	2.0 (n = 8)	3.5 (n = 24)
Chemistry Lab	2	0 (n = 4)	2.5 (n = 8)
Patient Room — Oncology	3	2.0 (n = 2)	6.3 (n = 9)
Cystoscopic/OR	4	NA	1.8 (n = 8)
Central Sterilizing and Supply	5	2.0 (n = 1)	2.0 (n = 4)
OB Recovery	6	1.0 (n = 5)	1.0 (n = 3)

SBS symptoms (from Figure 1) include: Headache, drowsiness, eye irritation, dry mucous membranes, sore throat, unexplained memory loss, itchy skin or rash, mental fatigue, and dry skin.

NA = Not Available

tion with one or two parameters such as thermal and air quality conditions may have adversely influenced occupants' perceptions of the lighting or acoustic conditions. It is also probable that occupants who were stressed by one or more environmental stressors may have been more susceptible to other stressors.

DISCUSSION

Comparison of the subjective data with the objective data ideally would be expected to illustrate correlations and would lend power to the conclusions about SBS. Results analyzed in this study indicate that objective and subjective findings may not always support each other in the determination of SBS. In comparing the objective and subjective data, it is important to recognize the many confounding factors and differences between functional categories. Figures 2 through 5 illustrate a site-by-site comparison of objective data and an associated perceived response. In these figures, dry-bulb and dew point temperatures (Table 2), particulate data (Table 3), and CO_2 data (Table 4) were used in comparison with perceived responses (Table 7).

Dry-Bulb Temperature. As shown in Figure 2, the mean dry-bulb temperatures for the Medical Records sites in Hospitals A and B were 24.2° and 25.9°C, respectively. The mean perceived responses to the temperatures in Hospitals A and B Medical Records were 4.6 and 2.6, respectively. Thus, occupants in Hospital A Medical Records found the temperature (24.2°C) nearly "acceptable," while Hospital B occupants perceived the temperature (25.9°C) as less than "somewhat acceptable." Hospital B's Medical Records area

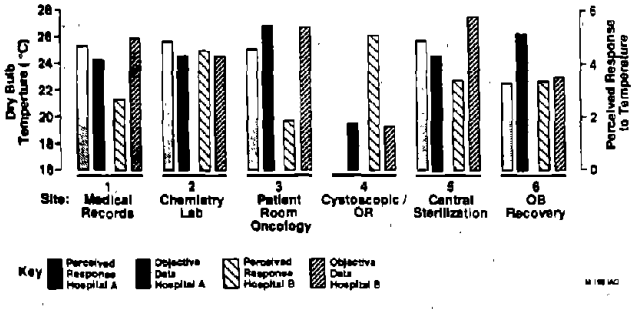

Figure 2 Comparative values between dry-bulb temperatures and perceived responses to temperature at six sites of two hospitals

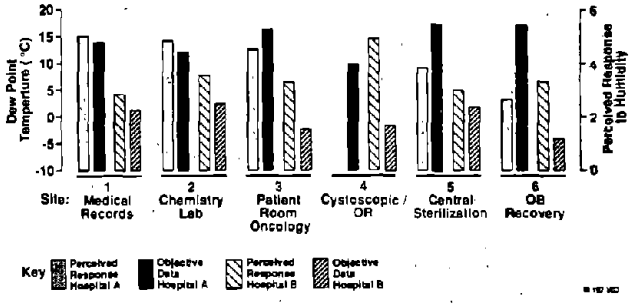

Figure 3 Comparative values between dew point temperatures and perceived responses at six sites of two hospitals

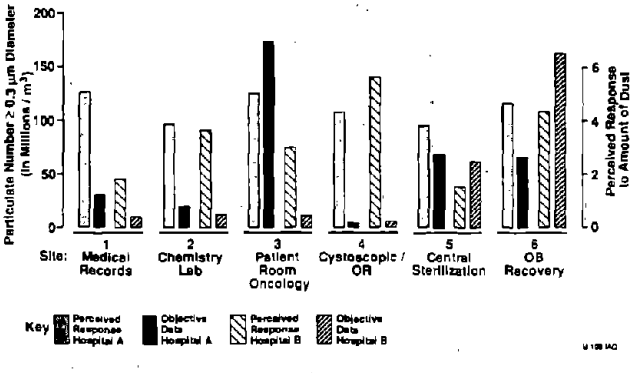

Figure 4 Comparative values between particulate numbers and perceived responses to amount of dust at six sites of two hospitals

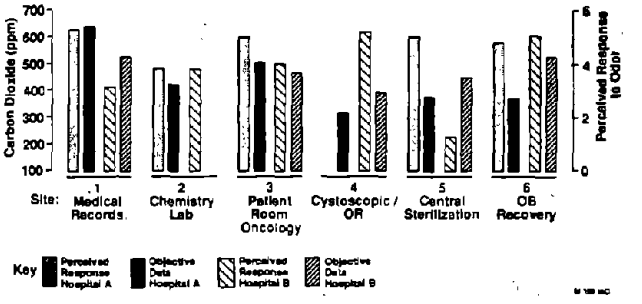

Figure 5 Comparative values between carbon dioxide concentrations and perceived responses to odor at six sites of two hospitals

TABLE 7

Comparison of Perceived Responses in Two Hospitals (Mean ± S.E.)

Parameter	Site 1 Medical Records		Site 2 Chemistry Lab		Site 3 Patient Room — Oncology	
	A	B	A	B	A	B
Temperature	4.6 ± 0.2	2.6 ± 0.2	4.8 ± 0.2	4.4 ± 0.2	4.5 ± 0.4	1.8 ± 0.1
Humidity	5.0 ± 0.0	2.8 ± 0.2	4.8 ± 0.2	3.5 ± 0.4	4.5 ± 0.4	3.3 ± 0.3
Air Movement	4.5 ± 0.3	2.0 ± 0.2	4.8 ± 0.2	3.4 ± 0.4	4.0 ± 0.0	1.9 ± 0.2
Odor	5.25 ± 0.2	3.1 ± 0.3	3.8 ± 0.8	3.8 ± 0.4	5.0 ± 0.0	4.0 ± 0.2
Amount of Dust	5.0 ± 0.0	1.8 ± 0.2	3.8 ± 0.5	3.6 ± 0.6	5.0 ± 0.0	3.0 ± 0.5
Amount of Tobacco Smoke	6.0 ± 0.0	5.7 ± 0.1	4.5 ± 0.4	6.0 ± 0.0	5.0 ± 0.0	5.2 ± 0.1
Loudness of Sounds	4.5 ± 0.3	4.4 ± 0.2	4.0 ± 0.5	4.6 ± 0.6	4.5 ± 0.4	2.7 ± 0.4
Pitch	4.5 ± 0.3	4.4 ± 0.1	3.8 ± 0.4	5.0 ± 0.3	5.0 ± 0.0	3.1 ± 0.4
Number of Noisy Distractions	4.3 ± 0.2	4.5 ± 0.1	4.0 ± 0.3	4.3 ± 0.4	4.0 ± 0.0	2.2 ± 0.3
Brightness of Lighting	4.3 ± 0.2	3.9 ± 0.3	4.3 ± 0.4	5.3 ± 0.3	5.0 ± 0.0	4.4 ± 0.3
Glare	4.0 ± 0.0	3.7 ± 0.3	4.8 ± 0.2	4.9 ± 0.4	4.0 ± 0.0	4.3 ± 0.3
Shadows	4.3 ± 0.2	4.0 ± 0.2	5.3 ± 0.2	4.6 ± 0.4	5.0 ± 0.0	4.9 ± 0.1
Overall	4.8 ± 0.2	2.8 ± 0.2	4.3 ± 0.4	4.3 ± 0.2	5.0 ± 0.0	3.1 ± 0.1
	S = 2 N = 8	S = 8 N = 24	S = 1 N = 4	S = 4 N = 8	S = 1 N = 2	S = 3 N = 9

S = # of Subjects
N = # of Responses (i.e., subjects × replicates)

Parmeter	Site 4 Cystoscopic/OR		Site 5 Central Sterilization & Supply		Site 6 OB Recovery	
	A	B	A	B	A	B
Temperature	NA	4.5 ± 0.3	4.8 ± 0.2	3.3 ± 0.2	3.6 ± 0.5	3.7 ± 0.3
Humidity	NA	4.9 ± 0.1	3.8 ± 0.2	3.0 ± 0.6	2.6 ± 0.7	3.3 ± 0.5
Air Movement	NA	4.8 ± 0.2	4.3 ± 0.2	2.8 ± 0.4	4.2 ± 0.3	3.3 ± 0.3
Odor	NA	4.6 ± 0.3	4.5 ± 0.2	1.3 ± 0.2	4.8 ± 0.2	5.0 ± 0.0
Amount of Dust	NA	4.8 ± 0.3	4.8 ± 0.2	1.5 ± 0.3	4.6 ± 0.4	4.3 ± 0.3
Amount of Tobacco Smoke	NA	5.9 ± 0.1	5.0 ± 0.0	6.0 ± 0.0	5.4 ± 0.4	6.0 ± 0.0
Loudness of Sounds	NA	5.1 ± 0.1	5.0 ± 0.0	4.0 ± 0.6	4.2 ± 0.3	4.3 ± 0.3
Pitch	NA	5.1 ± 0.1	5.0 ± 0.0	3.8 ± 0.8	4.4 ± 0.2	4.3 ± 0.3
Number of Noisy Distractions	NA	5.1 ± 0.1	4.0 ± 0.0	3.5 ± 0.8	4.2 ± 0.2	4.7 ± 0.3
Brightness of Lighting	NA	5.3 ± 0.2	5.0 ± 0.0	5.5 ± 0.3	5.0 ± 0.0	5.0 ± 0.5
Glare	NA	5.1 ± 0.1	4.3 ± 0.4	5.0 ± 0.4	4.6 ± 0.2	4.7 ± 0.3
Shadows	NA	5.1 ± 0.1	4.8 ± 0.2	4.5 ± 0.3	4.4 ± 0.2	4.7 ± 0.3
Overall	NA	5.1 ± 0.1	4.8 ± 0.2	4.3 ± 0.3	4.6 ± 0.2	4.0 ± 0.0
	S = 0	S = 4 N = 8	S = 1 N = 4	S = 2 N = 4	S = 4 N = 5	S = 1 N = 3

S = # of Subjects
N = # of Responses (i.e., subjects × replicates)
NA = Not Available

was too warm for its occupants.

In the chemistry labs, there was close agreement between nearly identical temperatures and perceived responses. However, in the patient room-oncology sites there were larger differences in perceived response to similar temperatures.

Differences in acceptability of temperature between functional sites are also shown in Figure 2. In the operating room of Hospital B, the temperature of 19.1°C received nearly "acceptable" perceived scores compared to the chemistry lab, which had a similar perceived score but a higher temperature of 24.4°C. This suggests there may be a range of acceptable temperatures within a hospital and the acceptable temperature is probably associated with, but not limited to, the occupants, their activities, their expectations, and the space's processes.

Dew Point Temperature. As shown in Figure 3, the non-problem Hospital A demonstrated nearly acceptable dew point conditions in three sites (Medical Records, chemistry labs, and patient room-oncology). However, mean dew point temperatures in Central Supply (17.2°C) and the OB recovery room (17.0°C) were perceived as less than "somewhat acceptable" (3.8) and less than "somewhat unacceptable" (2.6), respectively. These dew point temperatures (i.e., relative humidities of 64% and 57%, respectively) were the highest recorded in Hospital A and may reflect perceptions bordering on unacceptable conditions within Hospital A, especially in conjunction with the higher temperatures found in these areas.

In Hospital B, the comparisons between dew point temperatures were not so clear. Dew point temperatures were below 2.1°C for all functional areas and perceived responses of these dew point temperatures ranged from "somewhat unacceptable" (2.6) to "acceptable" (4.9). "Acceptable" conditions for dew point temperature were reported in the operating room of Hospital B; similar dew point conditions were found at the other sites of Hospital B, but were perceived as approaching "somewhat unacceptable." Again, the occupants, their activities, their expectations, and the processes in the area may have influenced the occupant responses.

Particulates. As seen in Figure 4, there is a trend for an inverse relationship between the number of particulates ≥ 0.3 μm diameter/m³ of air sampled and the perceived amount of airborne dust in occupied spaces. In other words, the lower the particle count at a functional site, the higher the acceptability. However, an interhospital comparison between objective and subjective measures is not as clear. Data from four of the five sites where comparisons could be made indicate that the particle counts were lower at Hospital B than at Hospital A, yet the responses at three of the sites at Hospital B were lower than the corresponding responses at Hospital A. These findings illustrate that within paired functional sites discrepancies between objective and subjective evaluation of airborne particulates are likely. At this time, it is not clear why these discrepancies exist: they may be due to imprecise measurement techniques, or they may be due to factors such as different standards of acceptability or to increased sensitivities from exposure to one or more other stressors.

Carbon Dioxide. Carbon dioxide concentrations were compared with perceptions of odor, as shown in Figure 5. In the four paired sites with complete CO_2 data, no association between CO_2 concentrations ranging from approximately 319 to 639 ppm and occupant perception of odor was apparent. If CO_2 were used as a surrogate to indicate the presence of human occupancy odors (primarily body odors) and no other sources of odor were present, then it would be expected that low CO_2 concentrations would be related to acceptable air quality in terms of odor. The CO_2 data compared with occupant perceptions do not confirm this hypothesis. CO_2 was not a reliable objective measure for comparison with the perception of odors at the relatively low concentrations observed in these two hospitals.

VOC. A comparison of VOC by matched site with occupant response to odor was not attempted due to lack of VOC data from Hospital A. Interestingly, results from targeted VOC indicated concentrations below documented odor recognition threshold concentrations, with the exception of limonene.

Overall Comparison. With the exception of Hospital B's dew point temperatures, all of the objective measures met accepted environmental and health evaluation criteria. However, results indicated that employees of Hospital A perceived environmental conditions to be more acceptable than did employees of Hospital B, and that SBS symptoms were reported with less frequency in Hospital A. The smaller deviation in Hospital A of objective measures from acceptable performance criteria (e.g., ASHRAE Standard 55-1981) tended to result in more acceptable overall subjective responses from the staff.

The differences in objective measures between the two hospitals were less than had been expected. In some functional categories of Hospital A, problems associated with SBS were identified, whereas several functional categories of Hospital B operated without obvious problems. The most notable differences between the two hospitals were in overall management and organization. In Hospital A, the importance of maintaining the physical plant was recognized by investing in a strong engineering staff. The competency of this staff was respected by the administrative and medical staffs and problems were effectively dealt with in a cooperative manner. Conversely, in Hospital B, the importance of the physical plant was overlooked, investment in the physical plant was minimized, competence of internal engineering staff was not emphasized, and outside service contracts were relied upon to an excessive extent. The competency of this staff was questioned by the medical and administrative staffs and environmental problems often persisted for months, resulting in adversarial relationships.

CONCLUSIONS

The results from these two field investigations and other studies reported in the literature lead us to the following conclusions:

1. Perceived responses of occupants are frequently more sensitive indicators of indoor air quality problems than are the objective measures conventionally relied upon for exposure evaluation. Reliance on objective data alone may not adequately identify the scope of the indoor air quality problem.
2. Problem areas may be found in "healthy buildings," while acceptable areas may be found in "sick buildings."
3. The management procedures selected to operate and maintain physical facilities are important not only in ensuring acceptable and economical performance of the systems, but in providing for a sense of confidence and well-being among those who are exposed to the environmental conditions.
4. Effective diagnostic protocols for buildings should incorporate observations, investigation of management strate-

gies, measurement of environmental variables, and perceived responses to the environmental conditions as a basis for system evaluation, predictions of future system performance, and recommendations for improvements.

5. Scientifically designed experimental studies should be conducted to test the relationship between objective and subjective measures in "sick" and "healthy" buildings.

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DISCUSSION

Gyan Rajhans, Health and Safety Support Services Branch, Ontario Ministry of Labour, Ottawa, Ontario, Canada: What were the ventilation rates in the various rooms of the hospitals? Were the operating rooms equipped with scavengers?

V.L. Putnam, Honeywell Indoor Air Quality Diagnostics, Golden Valley, MN: The derived occupant-normalized ventilation rates are provided in Table 5 of the paper. All of the derived ventilation rates were two to six times higher than the minimum values required in ASHRAE Standard 62-1981 or proposed in 62-1981R. Both hospitals were equipped with scavenger systems in the operating rooms.

Carl Lawson, LRW Engineers Inc., Tampa, FL: In the operating rooms, were there any problems with air and ventilation controls and in maintaining the operational guidelines?

Putnam: Briefly, Hospital A met the objective performance criteria established by IAQD; unfortunately, we were not able to obtain data on the occupant perceptions of the cystoscopic site. Hospital B did not meet the thermal evaluation criteria (the dry-bulb and dew point temperatures were too low); however, the staff found the thermal conditions to be acceptable. The systems serving the operating rooms of Hospital B were operating very close to their design flow capacities and the operating room site was operating with slightly less than the design value of 15 air changes per hour.

THE NEW COMFORT EQUATION FOR INDOOR AIR QUALITY

P.O. Fanger, D.Sc.
ASHRAE Fellow

ABSTRACT

For more than a century, ventilation standards have been based on Pettenkofer and Yaglou's classical theory that the human being is the dominant polluter in non-industrial buildings. Unfortunately, the existing standards do not prevent serious complaints concerning air quality in many buildings. A new philosophy of ventilation has been introduced acknowledging all pollution sources (materials, furniture, systems, etc.) in addition to bioeffluents and smoking caused by humans. This is accomplished by the olf and the decipol, the new units for perceived air quality. The units are used in a new comfort equation for indoor air quality. The comfort equation prescribes the ventilation required to obtain a given air quality (in decipol) in a space with a given pollution load (in olfs). The equation prescribes more ventilation than present standards or a reduction of the hidden olfs that ruin the air in many existing buildings. The comfort equation establishes a rational basis for future ventilation standards.

INTRODUCTION

The quality of indoor air is frequently unacceptable. Many people are bothered by the air they breathe and feel relieved when they get outdoors. This dissatisfaction has been documented in hundreds of detailed field studies in offices, schools, dwellings, and other non-industrial buildings in Europe, North America, and Japan (Melius et al. 1984; Kroling 1985; Valbjorn and Skov 1987; Komine et al. 1987; Wilson and Hedge 1987). The complaints include the perception of stale and stuffy air, irritation of mucous membranes, headache, lethargy, etc. These complaints are sometimes called the sick building syndrome (WHO 1983).

The complaints are not confined to a few special buildings, for they occur in most indoor spaces. There are, however, wide variations in the percentage of occupants who are bothered.

In some buildings there are obvious reasons for the poor air quality. The air supply may, for instance, be less than designed. But the frustrating fact is that most of the buildings studied in different parts of the world complied with existing ventilation standards and concentrations of measured contaminants were several orders of magnitude below any conceivable limit. Nevertheless, typically 20%, 40%, or 60% of the occupants found the air unacceptable.

The purpose of a ventilation standard is to provide acceptable air for the occupants. If this is not achieved there must be something wrong with the existing standards. Their basis is still the philosophy of Pettenkofer (1858), who founded modern hygiene, and the classical studies of Yaglou et al. in 1936. Their experiments on human bioeffluents have had a fundamental influence on ventilation standards in this century. In offices, assembly halls, and other similar non-industrial spaces it has been assumed implicitly that man was the predominant or exclusive polluter. Required ventilation was therefore specified per occupant. Some recent standards do refer to other pollution sources or single pollutants. But, for practical applications, they still assume that rooms and ventilation systems are absolutely clean and do not contribute to air pollution.

Recently Fanger et al. (1988) have identified severe pollution sources in spaces and ventilation systems by studying both occupied and unoccupied office buildings. The introduction of the olf unit (Fanger 1988) made it possible to quantify and compare different types of pollution sources. On average, human bioeffluents were found to comprise as little as 13% of the pollution sources. Materials in spaces and ventilation systems, ignored for a century as pollution sources in standards, were the major cause of the rather poor air quality observed in many of the 15 office buildings investigated. These hidden olfs are believed to be the main reason for the sick building syndrome.

In the present paper a new philosophy of ventilation is introduced considering all pollution sources present. This philosophy is quantified in a new comfort equation for indoor air quality. The equation is based on the olf and the decipol, the new units which integrate the pollutants in the air in the same way as they are perceived by human beings (Fanger 1988). The idea is to express all pollution sources in olfs. For a total pollution load in a space it is then possible to calculate the ventilation required to obtain a desired air quality.

Comfort Equation for Indoor Air Quality

The use of the olf and decipol units makes it possible to establish a pollution balance for the air in a space (see Figure 1). The following equation expresses that the pollution emit-

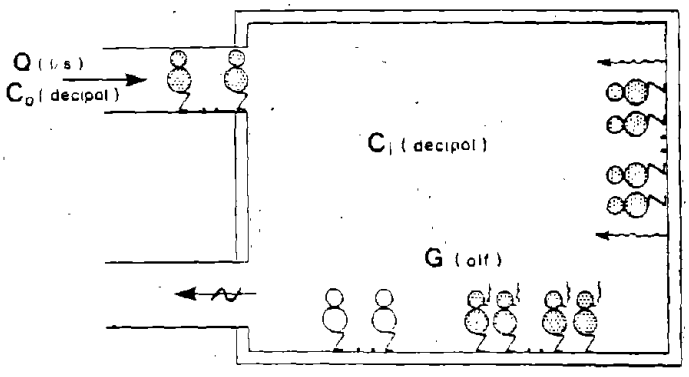

Figure 1 A space with total pollution sources G and perceived air quality C_i, ventilated by a flow of outdoor air Q with the air quality C_o

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TABLE 1

Perceived Outdoor Air Quality

	decipol
During smog episodes	> 1
In cities with moderate air pollution (Fanger et al. 1988)	0.05–0.3
On mountains or at sea	0.01

ted from the pollution sources in the space is taken up by the outdoor air supplied to the space.

$$C_i = C_o + 10\frac{G}{Q}$$

where

C_i = perceived air quality in the space (decipol)
C_o = perceived air quality outdoors (decipol)
G = pollution source strength in the space and the corresponding ventilation system (olf)
Q = outdoor air supply = ventilation rate (L/s)

For design purposes it is usually the required ventilation that needs to be determined and the equation is therefore rearranged in Figure 2. The relation between indoor air quality in decipol and percentage of dissatisfied is also given in Figure 2 (Fanger 1988).

The model in Figure 2 is the new comfort equation for indoor air quality. For any desired perceived indoor air quality, i.e., percentage of dissatisfied, the comfort equation determines the ventilation required to handle the total pollution source strength in the space. The perceived outdoor air quality is included in the model and should be estimated to determine the required ventilation.

The comfort equation may also be used to predict the air quality in a space (in decipol or percentage of dissatisfied) when the pollution source strength and the ventilation rate are known. The comfort equation may furthermore be used to determine experimentally the source strength in olfs in a space by measuring the outdoor air supply and by a judgment of the air quality indoors and outdoors by a panel (Fanger et al. 1988).

The comfort equation applies for steady-state conditions and complete mixing of the air in the space. A corresponding equation for transient conditions and any ventilation efficiency can easily be set up.

COMFORT EQUATION FOR INDOOR AIR QUALITY

$$Q = 10\frac{G}{C_i - C_o}$$

$$C_i = 1\,12(\ln(PD) - 5.98)^{-4}$$

where Q = ventilation rate (l/s)
G = total pollution sources (olf)
C_i = perceived indoor air quality (decipol)
C_o = perceived outdoor air quality (decipol)
PD = percent dissatisfied (%)

Figure 2 The comfort equation for indoor air quality

TABLE 2

Estimated olf Loads in Offices per m² Floor Area

Pollution sources	olf/m²
Occupants (one person per 10 m²)	
Bioeffluents	0.1
Additional load from 20% smokers	0.1
40% smokers	0.2
60% smokers	0.3
Materials and ventilation system	
Average in existing buildings	0.4
Low-olf buildings	0.1
Total load in office buildings	
Average in existing buildings, 40% smokers	0.7
Low-olf buildings, non-smoking	0.2

A basic idea in ventilation standards since Pettenkofer and Yaglou has been that people should perceive the air quality acceptable from the first moment they enter a space. It was essential that the first impression of the air was good. It was felt to be rather unrealistic telling people to disregard their first negative impression of the air quality and instead to wait some time until they became adapted to the pollution, as the air would be more acceptable then. The present comfort equation honors the idea concerning the first impression. The equation is based on a judgment of air quality just after entering a space.

It is essential to underline that the comfort equation predicts how the air is perceived. Some contaminants like radon and carbon monoxide are not perceived but may still present a health risk. Such contaminants should be considered separately.

Future Ventilation Standards

The comfort equation for indoor air quality may be used as a rational basis for future ventilation standards. It acknowledges for the first time all pollution sources, not just human bioeffluents and smoking, and it quantifies for the first time the quality of indoor and outdoor air as perceived by human beings.

The first step in a ventilation standard is to determine the desired air quality in the space to be ventilated. This is already done in the present ASHRAE ventilation standard (ASHRAE 1989), which specifies that the air quality should be acceptable to 80% of the occupants. This corresponds to 20% dissatisfied or 1.4 decipol. But a future standard may very well specify different air qualities for spaces with different applications.

The next step is to estimate the quality of the outdoor air available for ventilation of the space. In many cases the perceived outdoor air pollution is negligible compared to the indoor level. Table 1 lists some measured and estimated orders of magnitude of perceived outdoor air quality, but further data should be collected for typical locations and different heights above the ground. If the outdoor pollution is severe, it may be necessary to clean the outdoor air before it is suitable for ventilation.

The third step requires an estimation of all the pollution sources in the space and the corresponding ventilation system. The total olf load in the space should be calculated. Table 2 shows, as an example, estimated olf loads in offices per m² floor area. There is a contribution from the bioeffluents of the occupants. That is straightforward, i.e., 1 olf per person according to the olf definition. With 0.1 persons per m², the

TABLE 3

Ventilation Requirements in Office Buildings*

	L/s m²
Comfort equation (indoor air quality = 1.4 decipol)	
Existing buildings (0.7 olf/m²) smoking	5
Low-olf buildings (0.2 olf/m²) non-smoking	1.4
ASHRAE Standard 62–89 (ASHRAE 1989)	0.8
Nordic Guidelines, NKB (NKB 1981)	
smoking	1.0
non-smoking	0.4
DIN 1946 Standard, large offices (DIN 1983)	
smoking	1.9
non-smoking	1.4

*Assuming 0.1 person/m² and negligible outdoor air pollution.

bioeffluents contribute 0.1 olf per m² floor area. If smoking is permitted, there is an additional contribution, estimated on the basis of studies by Cain et al. (1983). For 40% smokers, which is a typical figure in Europe, this corresponds to an additional 0.2 olf/m². In North America less than 30% of occupants smoke, but each one smokes a larger number of cigarettes. So the average source strength of smoking is also around 0.2 olf/m² in North America.

The estimated pollution loads from materials plus the ventilation system are based on a field study by Fanger et al. (1988) in 15 randomly selected office buildings in Copenhagen. They found extensive pollution sources in the unoccupied buildings. The average pollution load was 0.4 olf/m², with a range of 0.1 to 0.9 olf/m². The pollution originated from all types of building materials, furniture, carpets, books, office machines, etc., and a major contribution came from the ventilation systems. As a first rough estimate of pollution sources from materials and ventilation systems in existing office buildings it is proposed to use the figure 0.4 olf/m².

For future design of office buildings it is recommended that strict control be kept of all materials used, that ventilation systems be designed with a low olf value when new, and that a rigorous maintenance scheme be prescribed to keep it low during its lifetime. In this way it is estimated that low-olf office buildings can be constructed with a pollution load around 0.1 olf/m² from materials and the ventilation system. This corresponds to the best buildings found in the Copenhagen study. Further field studies on olf values of a wide range of unoccupied, existing, and future buildings in different parts of the world are recommended.

The present estimates of pollution loads in olf/m² are analogous to rough estimates of heating or cooling loads in buildings expressed in W/m². A more detailed analysis of the thermal load requires information on the insulation of the various building components, etc. Similarly, a more detailed analysis of pollution sources in a space will require information on olf values of single materials in spaces and of components of ventilation systems. Such an olf catalog does not yet exist, but will be useful for future design and selection of materials.

Table 2 also gives an estimate of the total pollution load in office buildings. For an average of existing office buildings with 40% smokers the total pollution load from occupants, smoking, materials, and ventilation systems is 0.7 olf/m². In low-olf office buildings with no smoking, the total load is only 0.2 olf/m².

Ventilation requirements for office buildings may now be determined by the new comfort equation. To obtain an indoor air quality of 1.4 decipol (20% dissatisfied), a ventilation rate of 5 L/s m² is required for average existing office buildings (Table 3). This is three times higher than prescribed by any existing ventilation standard (Table 3). Such an increase in ventilation is *not* recommended, but rather the obvious alternative, i.e., to reduce the unnecessary hidden olfs. This will, at the same time, improve indoor air quality, decrease required ventilation and energy consumption, and diminish the risk of draft.

In low-olf buildings, the ventilation requirement is 1.4 L/s m² (Table 3). This ventilation rate is of the same order of magnitude as prescribed by some of the standards. The key to obtaining an acceptable indoor air quality at a reasonable ventilation rate is to control the olf load in the building at a low level. The design, development, and maintenance of low-olf buildings is a fascinating challenge for the future. It is an obvious way of improving indoor air quality, and a promising method of preventing sick buildings.

CONCLUSIONS

- A new philosophy of ventilation is introduced. The philosophy is quantified in a new comfort equation for indoor air quality based on the new units—olf and decipol.
- The comfort equation prescribes the ventilation required to obtain a desired perceived air quality (in decipol) in a space with a given pollution load (in olfs).
- The comfort equation acknowledges for the first time all pollution sources, not just human bioeffluents and smoking, and it quantifies for the first time the quality of indoor and outdoor air as perceived by human beings.
- The equation prescribes more ventilation than present standards, or a reduction of the hidden olfs ruining the air quality in many existing buildings.
- The comfort equation establishes a rational basis for future ventilation standards.

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DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: Do you feel the human element is a better form of test rather than instrumentation due to the repeatability or storing data for future use? With instrumentation, the reading should be more precise. Could you carry this a little further?

Fanger: It is not a new idea to use panels to judge air quality. Yaglou's classical work on bioeffluents and tobacco smoking was based on panels, and ventilation standards all over the world are based on his work. What I propose is that the pollution from all other sources also be judged by a panel. Chemistry has never played a significant role for ventilation practice or ventilation standards in non-industrial buildings. The reason is that the chemical composition of the air seldom allows us to predict whether the air is felt fresh and pleasant or irritating, stale, and stuffy. This has been documented in thousands of field studies throughout the world. Hopefully, a decipol meter will be developed some day.

Jerry Wesolowski, California Department of Health, Berkeley, CA: If building ventilation rates were designed using your comfort equation, how would one ensure protection from those pollutants that are not perceived, such as radon?

Fanger: It is required to consider such contaminants separately. Radon is a problem in some houses. In commercial buildings, the concentration of chemicals in the air is typically several orders of magnitude below the TLV-values. The comfort equation only considers the pollutants that make people dissatisfied and likely to complain.

Charlene Bayer, Georgia Tech Research Institute, Atlanta, GA: Have you considered the liability issues of using human subjects as a testing procedure instead of using instrumentation? There is a difference between using this type of panel and using a panel in a food testing procedure. It is doubtful that food tasting will cause any adverse effects other than a bad taste. In your model, you are taking people into areas which may cause various levels of discomfort, irritation, and toxicologically and other potentially adverse health effects (known or unknown), and you are knowingly doing this. The potential liability aspects could be horrendously damaging.

Fanger: I appreciate your warning. I am not a lawyer, but as long as we only expose our panel for a few moments, the risk should be very low compared to the occupants spending their entire working lives in the actual building.

Larry C. Holcomb, Holcomb Environmental Services, Olivet, MI: Panels of persons for detecting odors may be of value if methods are provided for training. As a toxicologist, I object to Mr. Fanger's reference to 4000 to 8000 chemicals that he suggests impact air quality and may present adverse health effects. I believe that we need to concentrate realistically on those substances that may have a health impact. These represent, in most cases, very few compounds. We should concentrate not just on risk but on significant risk identification.

Fanger: I think you misunderstood me. I claimed that typically there are thousands of compounds present in the air in commercial buildings; tobacco smoke alone contributes with 5000 compounds. But they are usually present in very low concentrations, several orders of magnitude lower than the TLV-values. The toxicologist would usually judge such air to be harmless. If 50% of the occupants still claim that the air is irritating, stale, and stuffy, it is a sensory response involving two senses—the general chemical sense (sensitive to irritants) and the olfactory sense (sensitive to odorants).

P.M. McNall: By using only "visitor" (first reaction) criteria, this equation, when developed, will indicate ventilation rates which will then be impracticably high. Wouldn't "occupant" (long-term) reactions often be more practically appropriate and result in more practically achievable ventilation rates?

Fanger: Since Yaglou the aim has been that the first impression of the air after entrance into a space should be acceptable. I do not recommend high ventilation rates. I prefer to avoid or remove high-olf materials wherever possible.

DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: What type of filtration system do you recommend other than using the personal touch?

Ole Fanger, Technical University of Denmark, Lyngby, Denmark: It is too early to tell. But we have seen cases where the filter material itself contributes to the air pollution. The dust collected at the filter also contributes to a certain extent to ruin the quality of the supply air.

EMISSION PATTERNS OF UNVENTED COMBUSTION DEVICES BURNING LIQUID AND GASEOUS FUELS

V. Haraprasad **J.M. Dave**

ABSTRACT

Emission factors of important criteria pollutants like NO_x, SO_2, CO, particulate matter, and HCHO were determined at different burn rates both with and without a pan, in the case of a kerosene wick stove and an LPG stove burning a 55:45 mixture of propane-butane gases. Findings reveal certain patterns in the evolution of these pollutants which are affected by the use of the pan. Also, there appears to exist a range of burn rates wherein the evolution of some pollutants is at an optimum. Non-stoichiometric SO_2 emissions, as well as the factors affecting CO evolution, are discussed. The paper highlights factors affecting source emissions and outlines practical measures for abatement of emissions at the source.

INTRODUCTION

The source emissions, termed *S*, in indoor air quality models, are assumed to remain constant and are expressed in volumetric or gravimetric units of the concerned pollutant per unit time (Turk 1963; Moschandreas et al. 1987). However, it had been shown that for unvented combustion devices *S* varies greatly depending on appliance type, primary aeration rate, fuel input rate, appliance use pattern, fuel type, etc. (Billick et al. 1984). In order to study some of the factors affecting source emissions, as well as to acquire a data base, two unvented combustion devices were chosen. One was a popular multiwick non-pressure kerosene stove (2.5 million users) and the second an LPG (liquefied petroleum gas) stove of a popular burner design (8 million users) both supposedly conforming to the specifications laid down by the Bureau of Indian Standards (I.S.2980 1979; I.S. 4246 1984).

The kerosene stove operates with a blue flame and gives high heat output, as in a gas stove. It has two concentric perforated cylinders between which the wicks emerge from the burner upon raising the wick lever. The annular space between the perforated cylinders serves to draw combustion air from either side for mixing with fuel vapors and for directing the flame upward.

EXPERIMENTAL DETAILS

The direct flue gas measurement technique (Yamanaka et al. 1979; Dave 1984) was adopted with an enclosed hood and duct assembly for capturing all the emissions, which were drawn out of the 100 mm diameter duct by means of a 100 mm diameter exhaust fan (Figure 1). The duct gas velocity was measured by a calibrated airflow meter sensor of 100 mm diameter, kept at right angles to the direction of duct gas flow (Figure 2). The typical duct airflows induced by the exhaust fan were of the order of 0.008 $m^3 \cdot s^{-1}$.

The experimental set-up was enclosed by a specially erected chamber to prevent reentry of exhausted gases into the duct. The sampled gases were also conducted out of the chamber. To verify whether all the emissions were collected by the hood, in-chamber background levels of the same pollutants were monitored for unusually high values arising from spillover of combustion gases into the chamber. The background concentrations were deducted from duct gas concentrations in arriving at the emission factors.

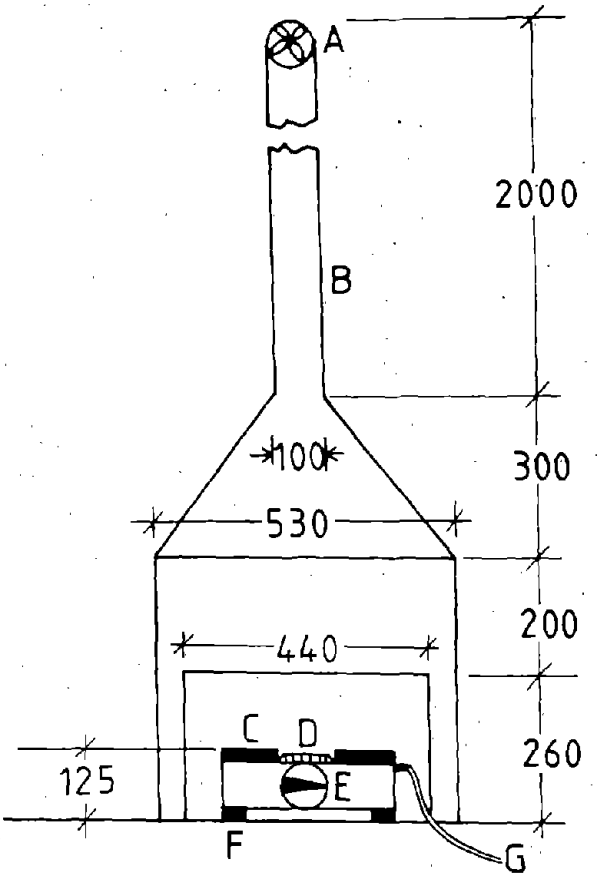

Figure 1 *Enclosed hood and gas stove in place. A-exhaust fan, B-duct, C-pan supports, D-burner, E-knob, F-grommets, G-rubber tubing to cylinder. All dimensions are in millimeters.*

All 28 samplings for the kerosene wick stove and 60 samplings for the LPG stove were obtained, both with and without a pan, at different burn rates. An aluminium pan that was 175 mm in diameter and 93 mm deep, weighing 280 g, and a predetermined thermal load of 1.5 L of water were used in samplings done with the pan in place. In the case of the kerosene stove, the emissions were studied at three different fuel levels, since the level of fuel in the tank was reported to affect the performance according to the operation manual of the stove. In the case of the LPG stove, two burners of different power ranges, as normally used in a dual-burner gas stove, were tested. The methods of analysis (Katz 1977) adopted for different pollutants are shown in Table 1.

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TABLE 1

Methods of Analysis Used for Different Pollutants

Parameter	Method of Analysis
Nitrogen dioxide	Saltzman's colorimetric method
Nitric oxide	Saltzman's colorimetric method after oxidation to NO_2
Sulfur dioxide	West & Gaeke's method
Formaldehyde	Chromotropic acid method
Carbon monoxide	MSA indicator tube method
Particulate matter	Gravimetric method using GF/C 47 mm filter

TABLE 2

Burn Rates of LPG for Burners Used in the Study

Burner	Setting	n	Burn rate of LPG Liquid g/h	Flame height cm
Big	Sim	4	50.50 ± 0.24	2 – 3
	Med	4	112.10 ± 1.85	8 – 10
	Max	4	239.02 ± 0.95	18 – 20
Small	Sim	4	47.11 ± 0.31	2 – 3
	Med	4	93.12 ± 2.01	8 – 10
	Max	4	158.07 ± 1.37	18 – 20

The MSA detector tube method was chosen due to practical difficulties in obtaining other instruments, using the NDIR technique, in the desired time frame. The emission factor determination, using this method, is outlined in Appendix A. A sampling period of one hour was adopted for all parameters. The flow measurement was done using calibrated rotameters or a soap bubble meter for flow rates below 0.005 $L \cdot s^{-1}$.

The fuel consumption rate was gravimetrically determined for the kerosene stove. In the case of the LPG stove, the burners were calibrated using a portable 5 kg LPG cylinder at three flame settings—minimum, medium, and maximum—in terms of grams of liquid-phase LPG consumed per hour at each setting. Only these settings were used in the study of emission factors. While it was not possible to replicate specific burn rates in the kerosene stove, it was comparatively easier in the gas stove. The standard deviation of the burn rates, at medium and maximum settings, is somewhat high as compared to the minimum setting for both burners (Table 2). This could be due to the absence of any clear-cut boundaries in the gas knob demarcating the medium and maximum flame conditions. In the "sim" setting, however, the simmer orifice controls the flow. The observed deviations here could be due to minor fluctuations in the flow of gas from the cylinder.

The burn rates were determined as described below:

The 5-kg cylinder was preweighed and connected to the stove by means of the pressure regulator. The regulator knob was opened with the stove knob still in the OFF position. A lighted match was brought near the burner and the stove knob turned on. The desired stove setting was always approached from the maximum setting. After operating the stove for the desired duration with the stove knob still in the ON position, the regulator knob was turned off and the residual gas allowed to burn in the stove. The cylinder was then disconnected and weighed again. From the difference in weights of the cylinder, gas consumption per unit time was calculated.

In the case of samplings done with the pan in place, the sampling was started soon after blue flame adjustment was made and the pan was placed on the stove. For samplings with an open flame, sampling was started soon after the stove was lit. The objective, in the latter case, was to estimate the total emissions without the pan. The pollutants emitted during the short period of lighting and blue-flame establishment, as in the case of the kerosene stove, were not monitored separately since they were found to be below detectable limits of the methods chosen for analysis.

The average net calorific values of 42,810 $kJ \cdot kg^{-1}$ of kerosene and 45,640 $kJ \cdot kg^{-1}$ of liquid phase LPG were used in calculating the emission factors in terms of $\mu g \cdot kJ^{-1}$. The sulfur content of the kerosene was determined as 0.07% by weight using the Raney Nickel method (IOM 121 1986) in a petroleum research facility. In fitting the emission pattern curves, linear, exponential, power, and logarithmic regres-

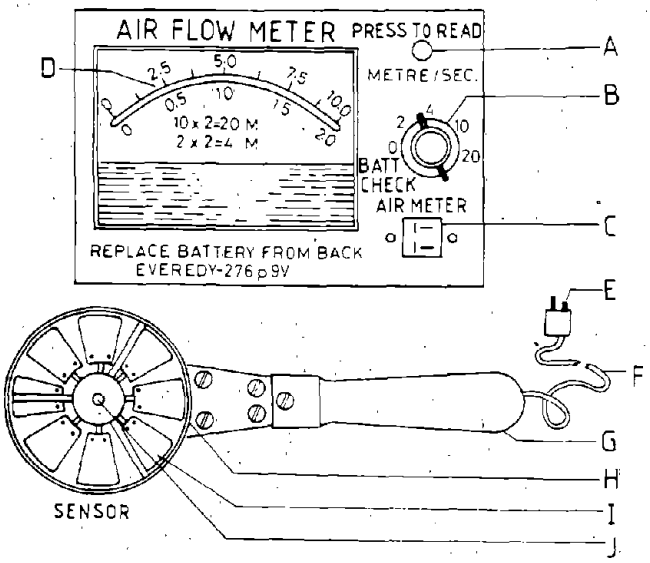

Figure 2 Main components of the airflow meter. A-press button switch, B-range selector, C-three-pin socket, D-indicator, E-three-pin plug, F-connecting cord, G-handle, H-magnet, I-angular vanes, J-bearings.

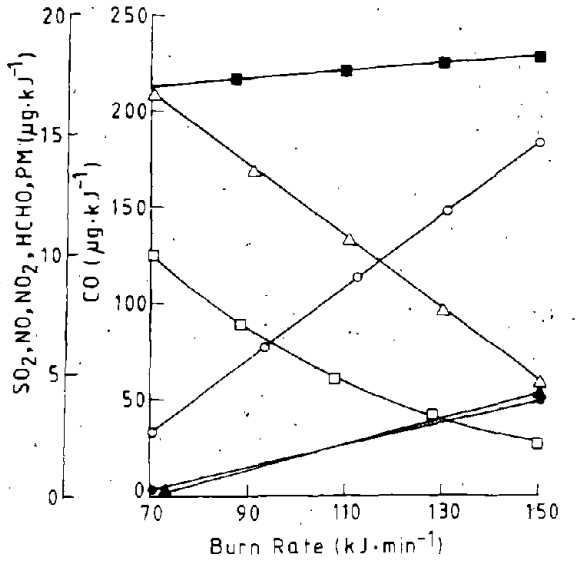

Figure 3 Emission patterns for open flame operation of kerosene wick stove. Pollutants followed by Pearson's r in parentheses: ● - HCHO (0.79), ○ - NO_2 (0.73), ▲ - NO (0.80), △ - CO (0.62), ■ - SO_2 (0.14), □ - PM (0.62).

sions were tested on a personal computer and the curve giving the best fit was chosen to represent the relationship between the two parameters.

RESULTS AND DISCUSSION

Referring to Figure 3, it can be seen that, with increasing burn rates, CO and particulate matter (PM) decreased, while all other pollutants showed an increase when the kerosene stove was operated without a pan. However, when the pan with a thermal load was used, the patterns changed, as shown in Figure 4. Here, except for HCHO and PM, all others showed an increase with increased burn rates. While the opposing trends of HCHO emissions in Figures 3 and 4 have something to do with the design of the combustion device, it may be seen that they are higher when the pan is used than they were with an open flame operation. The scattergrams corresponding to Figure 4 are given in Appendix B (Figure B-1).

Nitric Oxide

The formation of NO is known to be dependent on the peak temperatures achieved during combustion. If the duct gas temperatures (DGT) are considered as surrogates for peak flame temperatures achieved in the open flame operation of the kerosene stove, then NO generation had been somewhat commensurate with the DGT, until 110°C (Figure 5). The fluctuating DGT could be due to a combined effect of fluctuating combustion efficiencies of the stove as well as airflows through the duct. The drop in NO at 120°C could have been due to the fuel mixture becoming rich and off-stoichiometric beyond the corresponding burn rate. This might be due to a design limitation in the appliance. The subsequent rise in NO value, at a DGT of 162°C, indicates that much of the NO in this case could have been formed in the post-combustion reactions (Edwards 1974).

In comparison, NO values appear to be the same, or somewhat more, with the pan than without it. It is possible that the pan bottom acts as a damper for air currents, thereby maintaining the reacting gases at a high temperature for a longer period, resulting in higher NO emissions. This does not happen in the LPG stove, perhaps because the burner design is different.

Figures 6 and 7 depict that, in the LPG stove, while NO formation in an open flame has a high correlation with burn rate, the correlation is poor when the stove is operated with a pan. This might be due to the prevalence of off-stoichiometric conditions at higher burn rates, owing to the burner design.

It can be seen from Table 3 that NO emissions from the LPG stove are greater than kerosene stove emissions by about 4 times when operated without the pan, and by 5 to 23 times when operated with the pan. Also, for the same range of burn rates, the LPG stove (small burner) produces 3 to 7 times

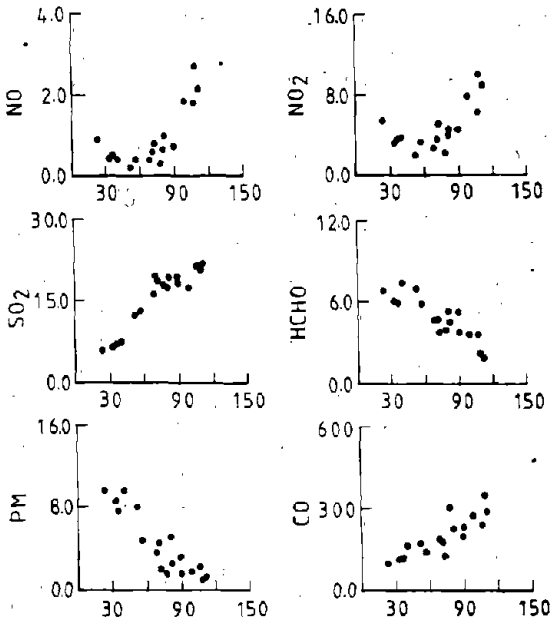

Figure B-1 Scatter diagrams of overall emissions ($\mu g \cdot kJ^{-1}$) against burn rates ($kJ \cdot min^{-1}$) for covered flame operation of kerosene wick stove

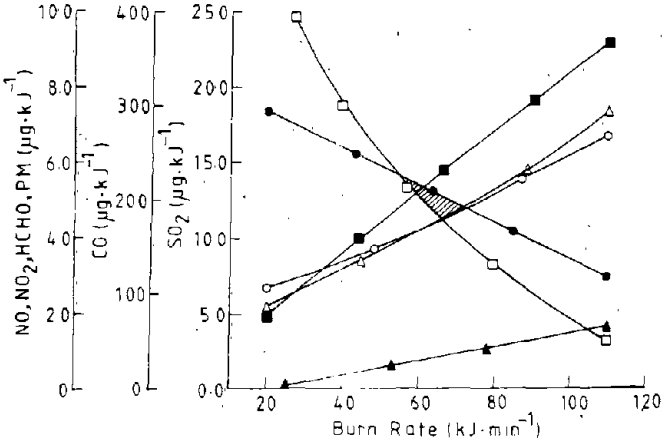

Figure 4 Overall emission patterns for covered flame operation of kerosene wick stove (combined for all three reservoir fuel levels). Pollutants (Pearson's r): ● - HCHO (0.88), ○ - NO_2 (0.64), ▲ - NO (0.70), △ - CO (0.87), ■ - SO_2 (0.96), □ - PM (0.92).

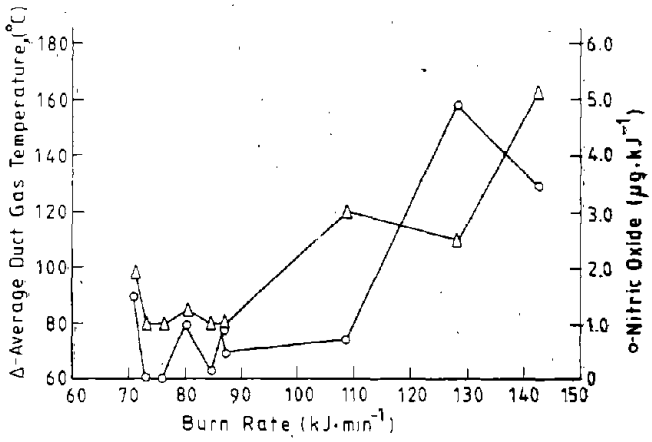

Figure 5 Fluctuations in duct gas temperatures and nitric oxide emissions

TABLE 3

Range of Emission Factors for Kerosene and LPG Stoves (ug kJ^{-1})

Stove/ Mode of Operation		NO	NO_2	SO_2	HCHO	PM	CO
K/WoP (n = 10)	Min.	0.0	2.1	14.00	0.0	4.52	96.1
	Max.	4.88	18.73	22.27	4.35	11.69	285.30
K6/WP (n = 6)	Min.	0.52	3.56	5.89	2.25	1.01	103.94
	Max.	2.72	9.72	20.50	6.82	9.61	346.55
K3/WP (n = 6)	Min.	0.38	2.85	6.59	2.02	1.11	118.48
	Max.	2.17	8.74	21.31	6.00	8.68	288.62
K1/WP (n = 6)	Min.	0.22	2.10	7.56	3.56	1.61	162.71
		1.80	6.16	20.89	7.34	9.67	296.45
LS/WoP (n = 12)	Min.	7.15	9.67	0.0	0.48	0.0	0.0
	Max.	13.30	16.60	0.45	0.84	0.31	4.54
LS/WP (n = 18)	Min.	6.07	9.17	Nil	0.52	0.0	5.40
	Max.	9.95	19.54		1.57	1.5	479.79
LB/WoP (n = 12)	Min.	4.28	10.71	0.0	0.0	Nil	0.0
	Max.	20.07	20.37	0.56	1.17		14.76
LB/WP (n = 18)	Min.	5.17	7.25	0.0	0.62	Nil	12.0
	Max.	15.34	22.88	0.19	1.11		527.28

n = number of samples; K- Kerosene Stove; WoP- Without a pan; WP- With a pan; LS- LPG small burner stove; LB- LPG big burner stove; K6, K3, K1- Fuel levels in centimeters in kerosene stove.

more NO without the pan, and 3 to 27 times more NO with the pan, than the kerosene stove.

Nitrogen Dioxide

When both oxygen and nitric oxide are present in the effluent gases, the nitric oxide will be oxidized to nitrogen dioxide as the gases cool. However, the rate is low and the residence time is much too short for the conversion to occur.

NO_2 may also be formed in the flame zone through the following reaction mechanism (Bowman 1975) in which the NO formed in the flame zone is rapidly converted to NO_2:

$$NO + HO_2 \rightleftharpoons NO_2 + OH \qquad (1)$$

This reaction is known to be fast at room temperature. NO_2 may also be formed due to flame quenching by a surface, e.g.,

$$NO + O \xrightarrow[\text{Surface}]{\text{Quench}} NO_2 \qquad (2)$$

In either case, the NO_2 formed may be converted back to NO via the reaction

$$NO_2 + O \rightarrow NO + O_2 \qquad (3)$$

which is also rapid at low temperatures (240–1800 K).

Thus, NO_2 exists only as a transient pollutant at flame

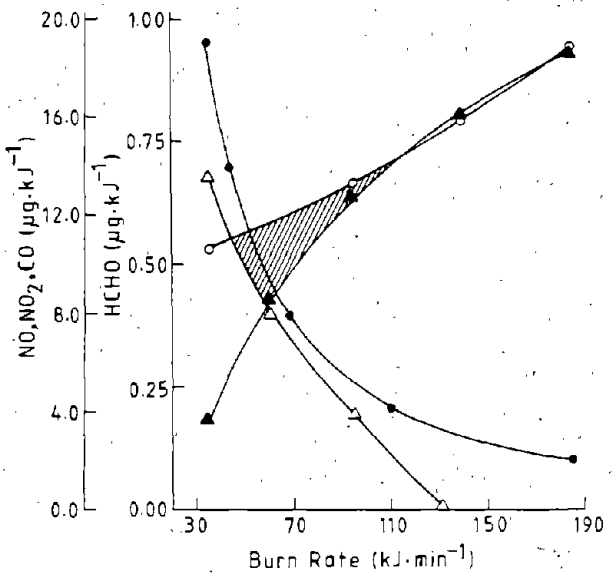

Figure 6 Emission patterns for open flame operation of LPG big burner stove. Pollutant (Pearson's r): ● - HCHO (0.83), ○ - NO_2 (0.98), ▲ - NO (0.99), △ - CO (0.77).

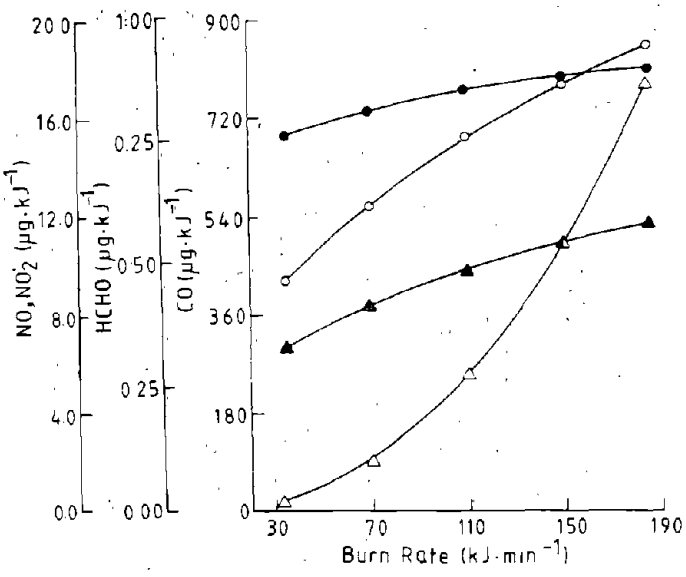

Figure 7 Emission patterns for covered flame operation of LPG big burner stove. Pollutant (Pearson's r): ● - HCHO (0.67), ○ - NO_2 (0.62), ▲ - NO (0.55), △ - CO (0.85).

conditions. For the NO_2 formed in the flame to persist in the effluent gases, it must be quenched before it is converted back to NO. Rapid mixing of the hot effluent gases that leave the combustion zone with the surrounding cool air might cause that quenching.

A comparison of Figures 3 and 4 reveals that NO_2 emissions are higher with a pan at lower burn rates. It is surmised that most of the NO_2 formation in the kerosene stove might be taking place via reactions shown in Equations 1 and 2 in the flame zone and by quenching at the interface between the flame front and the walls of the perforated cylinders through which combustion air diffuses. Reaction 2 may be dominating at the pan surface. The lower DGT, when the pan was used, could have served to quench the NO_2 formed in the combustion zone.

In the case of the big burner LPG stove, the NO_2 patterns are more or less the same, both with and without the pan (Figures 7 and 6). The correlation between NO_2 and burn rate, in the former case, is poor (Pearson's $r = 0.62$), possibly due to the prevalence of the off-stoichiometric conditions discussed earlier. NO_2 emissions from the LPG stove are about 1 to 5 times greater without the pan, and about 2 to 3 times with the pan than those from the kerosene stove.

Formaldehyde

In the kerosene stove, formaldehyde formation may take place in a region where the pyrolytic precombustion products react with the hot air to form the final combustion products. At this stage, if the mixing of air and fuel vapor is not complete, the intermediate products could be transported away from the combustion zone, preventing further oxidation. Thus, HCHO emissions are higher when a pan is used than with open flame operation. The use of a pan could be inhibiting the mixture of combustion air and the pyrolytic precombustion products, especially at lower burn rates. The mixing may be better at higher burn rates, resulting in lower HCHO emissions.

Formation of HCHO in an LPG stove could be due to the inner layers of the flame not getting enough secondary air. The emissions were, however, 4 to 6 times less than kerosene stove emissions (Table 3).

Particulate Matter

Particulate matter (PM) in the kerosene stove is mostly a product of pyrolytic precombustion reactions and is emitted, as such, without further oxidation when mixing is not complete, as may occur at lower burn rates. The poor correlation observed in Figure 3 could be due to fluctuating mixing conditions in the concentric perforated cylinders. The emissions were more without the pan than with the pan. This could be due to the pan acting as a barrier to the free flow of particles in the buoyant effluent gas. PM emissions from the LPG stove were negligible and sporadic. No conclusions could be drawn from the observations available.

Sulfur Dioxide

Any fuel containing sulfur emits sulfur dioxide when burned. Generally its combustion is complete and hence stoichiometric concentrations of SO_2 are expected in the emissions. However, in the present study, the SO_2 emissions recovered were found to be proportional to the burn rate used despite the maintenance of the same sampling efficiency throughout, as shown in Figure 8. There was good correlation (Pearson's $r = 0.93$) between burn rates and SO_2 emissions both with and without a pan.

The literature was scanned to find out if similar observations were recorded in any of the studies done earlier. Indications to the effect that not all the sulfur burned was recovered as such were given by Woodring et al. (1985). They burned fuel containing 0.04% sulfur, but the maximum SO_2 recovery was about 8 $\mu g \cdot kJ^{-1}$ as against the stoichiometric 17 $\mu g \cdot kJ^{-1}$. No reasons were advanced for this phenomenon.

Since sulfur oxides and particulates are generally synergistic, it was decided to find out if any correlation existed between the two parameters. As shown in Figure 9, a strong negative correlation (Pearson's $r = 0.92$) existed between SO_2 and particulate matter, i.e., the higher the particulate matter, the lower the SO_2 and vice versa. This, coupled with the fact that activated carbon is used as an adsorbent to remove sulfur oxides from waste gases (Slack and Hollinden 1975), has led to the conjecture that some of the SO_2 formed could be getting adsorbed onto the particulate matter.

The stoichiometric SO_2 for a sulfur content of 0.07% in

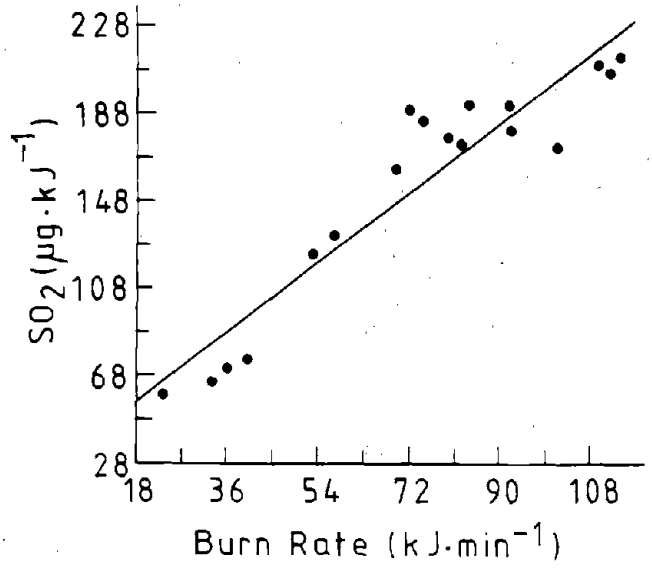

Figure 8 Correlation between burn rate and sulfur dioxide emissions (Pearson's r = 0.93)

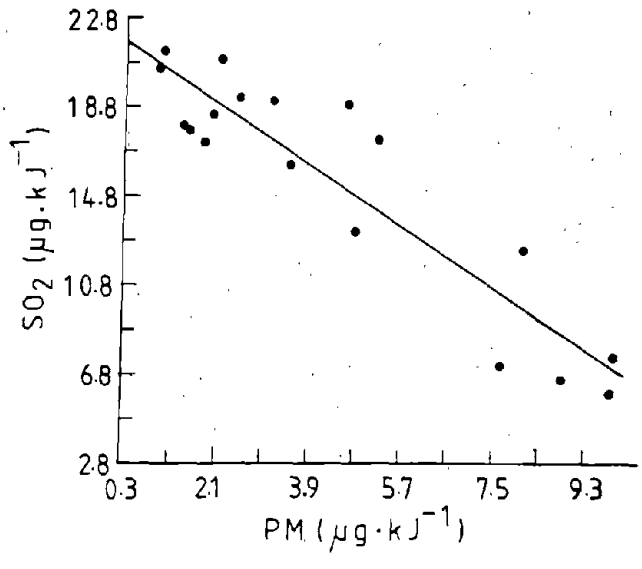

Figure 9 Correlation between particulate matter and sulfur dioxide emissions (Pearson's r = 0.92)

kerosene used in the present study was 32.7 $\mu g \cdot kJ^{-1}$. The maximum that could be recovered was 21.31 $\mu g \cdot kJ^{-1}$ at a burn rate of 110.91 $kJ \cdot min^{-1}$. It is presumed that the rest of the SO_2 could be getting adsorbed onto the particulate matter, in view of the strong negative correlation noticed between them and the fact that even atmospheric dust is known to adsorb SO_2 (Liberti et al. 1978; Tartarelli et al. 1978).

The range of SO_2 emissions from the kerosene stove is shown in Table 3. The emissions were more or less the same for the respective burn rate ranges. In the open flame operation, burn rates correlated better with SO_2 emissions per minute (Figure 10) than with SO_2 emitted per kilo Joule (Figure 3).

No pattern could be discerned in SO_2 emissions from the LPG stove. The only sulfur source in LPG are the mercaptans added to give it a pungent odour for easy detection of the leaking gas. The quantities added are very small. Some of the heavier gases, like butane, may contain sulfur in disulfide form, but that supposition should be verified by detailed investigation to determine the species of sulfur compounds. As compared to the kerosene stove, SO_2 emissions from LPG combustion are negligible and of no concern.

Carbon Monoxide

Carbon monoxide can be produced either when the fuel vapor is not properly mixed or when the mixture is fuel rich. In this study, it has been observed that CO can also result when the flame temperature is rapidly lowered at a surface (flame quenching), thereby disrupting the oxidation reactions progressing in the flame. For this reason, the CO emissions in open and covered flame operations cannot be compared using burn rate as a common criterion.

In open flame operation, CO generation takes place either due to improper mixing, as in the kerosene stove, or due to a lack of adequate primary air at low jet (sim) velocities, as in the gas stove. When a pan with a thermal load is used, the situation is different. Here, the rate at which the flame is quenched determines the rate of CO evolution. This was based on the observation that a good correlation (Pearson's $r = 0.88$) existed between CO emissions and the rate at which the latent heat of vaporization was lost to the atmosphere while boiling water, as shown in Figure 11.

Since the latent heat capacity of water is quite large (2270 $kJ \cdot kg^{-1}$), it is postulated that the flame is quenched at the interface with the pan bottom because of the almost instantaneous transfer of a significant part of its heat into the duct, in the form of water vapor. The steep temperature gradient arising at the interface of the pan surface when water is boiling could be responsible for the rapid quenching of the flame. This was supported by the fact that CO evolution was sluggish until the water started evaporating.

Another supporting observation noted was that when all the water in the pan evaporated dry, the CO evolution also dropped drastically. Since there was no water to absorb and release this heat in vapor form, the heat was radiated into the duct, raising the duct gas temperature. Kane (1950) also observed that CO production increased with increasing impingement on the pan bottom. The reason attributed to that finding was increased interference with secondary air entrainment as the impingement area increased, resulting in less complete oxidation of CO to CO_2. While this may explain CO generation in the gas stove, it does not hold for the kerosene stove.

All these observations seem to justify the conclusion that, when a stove is operated with a pan in place and a thermal load of water, irrespective of how efficient the combustion may be, CO evolution does take place. It is a function of the rate at which the flame gets quenched at the interface with the pan bottom. This may, however, depend on the pan bottom, its shape, size, material, and contents; in short, anything that changes the lower surface temperature of the pan.

For instance, when the pan contents were changed from water to sand, there was very little CO generation, as compared to water. CO generation was more rapid when an enameled white tray (360 by 300 by 60 mm) instead of an aluminium pan was placed over the LPG stove. The CO generation was even more rapid when a hemispherical aluminium pan was used. These aspects need further study, involving the measurement of surface temperatures and gas film tem-

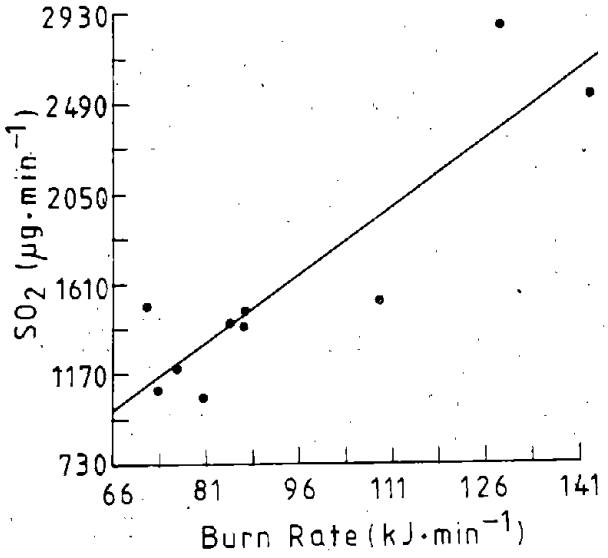

Figure 10 Correlation between sulfur dioxide emission rate and burn rate in open flame operation of kerosene stove (Pearson's r = 0.89)

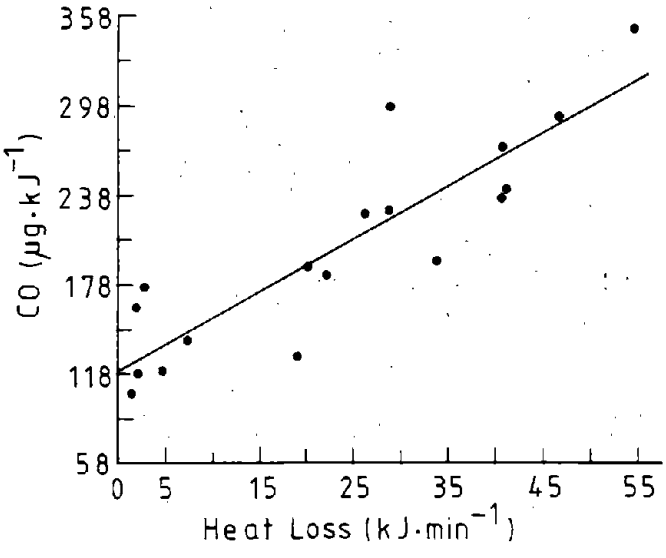

Figure 11 Correlation between carbon monoxide emissions and heat loss due to vaporization (Pearson's r = 0.88)

peratures. CO emissions in open flame operation are much higher with the kerosene stove than with the LPG stove (Table 3).

CONCLUSIONS

Several points emerge from this work. The first observation is that both the kerosene and LPG stoves emit pollutants which are harmful to health. While the kerosene stove dominates in SO_2, HCHO, and PM emissions, the LPG stove dominates in NO_x emissions. CO emissions are a common factor for both the stoves. Secondly, these emissions do fall into a pattern—increasing or decreasing, linear or curvilinear—in relation to burn rate and are affected by the use of a pan. Third, there could still be other factors that influence the emissions, as in the case of CO. Last, but not least, there appears to exist an optimum range of burn rates, especially in the case of the kerosene stove, as indicated by the shaded areas between which some pollutant emissions would be at an optimum (Figures 3 and 4). This optimum range is restricted to open flame operation of the big burner only in the case of the LPG stove (Figure 6).

It is to be cautioned that the emission patterns observed could be specific to the stoves and the pan used in this study. However, it throws open certain possibilities that might result in an abatement of emissions at the source. For instance:

a) The optimum range of burn rates observed from the emissions viewpoint could also exist in the unvented combustion devices (UCD) used in developed countries. This might help the manufacturers specify the optimum range of burn rates between which a UCD may be operated. Alternatively, for example, rate controllers may be installed on the gas manifolds for each burner, in the case of the gas stove. Whereas it is not possible to completely eliminate NO_x emissions, it may be possible to reduce them substantially by this measure.
b) In the light of preliminary findings about CO generation, it might be possible to evolve an ideal utensil a la pressure cookers, pans, etc., for adoption on a mass scale, taking into account the size, shape, and material of the utensil vis-a-vis the emissions. In doing so, the cultural and aesthetic factors will, of course, have to be borne in mind.

c) The findings on CO evolution indicate that CO generation can be substantially reduced if the contents of the pan are covered, so as to reduce heat loss. This is significant because, in an assessment study done on the knowledge and management practices of urban housewives in regard to cooking fuels, it was found that a gap existed between knowledge and its application in fuel use (Ogale and Chaturvedi 1985). In several cases, the reluctance to light a match took precedence over switching off the burner of a gas stove in between operations. Then there are other undesirable habits like using smaller diameter vessels, an unjustified preference to always use the big burner, operating the stove at full flame even after the contents come to a boil, boiling without a lid, using excessive water for cooking, clogged burners, etc. Keeping the above factors in mind, it may be feasible to evolve health education strategies aimed at proper usage of the stoves both from pollution and thermal efficiency points of view as well as to avoid exposure to the pollutants.

Certain conclusions can be drawn from the present study:

1. Stray emission factors reported in published literature are difficult to use in characterizing the pollutant release rate of combustion devices. The emissions must be studied with respect to the operational factors influencing the use of the devices and the specific pollutant emission rates, as in the case of SO_2 and CO.
2. Both the kerosene stove and the LPG stove have a significant pollution potential in homes. Since there are no viable alternative "clean" fuels at present, it is necessary to take a second look at the design of these innocent-looking devices from the pollution angle and make modifications in the appliance design.
3. The present study also indicated the intimate complicity of combustion phenomena in the formation of pollutants in flames. Hence any source emission modeling effort must incorporate a synthesis of pollutant chemistry and combustion science principles.

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APPENDIX A
METHOD OF CO DETERMINATION USING MSA DETECTOR TUBES

The indicator tubes, when fitted to the squeeze bulb and aspirated, were expected to show stains of different intensities corresponding to different volumetric percents of CO, depending on the number of squeezes; they were thus calibrated at a particular flow rate. In this case it was 0.1 liter per minute. Since the duct gas CO concentrations were not high enough to produce a stain in the tube in one or even five squeezes of the bulb (the maximum indicated on the color chart), it was decided to aspirate the gas through the tube at the same rate, 0.1 lpm, for an extended period of time until the stain showing 0.1% was achieved. This was done by connecting the CO indicator tube to the sampling system and plugging it directly into the G.I. duct. A thermocole (expanded polystyrene) sleeve was fitted to the tip of the tube going into the G.I. duct to prevent heating of the tube by hot gases. In each case, the time taken to reach 0.1% concentration stain was noted. This ranged from 5 to 60 minutes. Intermediate stain intensities were approximated to the nearest % CO concentration reading, or an average value was taken. All parameters measured at elevated temperature and pressure were reduced to their respective values at 25°C and 760 mm Hg. The concentration of CO in the duct was then calculated. As an example:

Assume that a 0.1% concentration was recorded in 10 minutes, at a flow rate of 0.1 liter per minute. The quantity of air sampled in 10 minutes is, therefore, 1 L. The standard volume of the sample is calculated to be 0.9 L at 25°C and 760 mm Hg. Therefore, the 0.1% concentration which should have been achieved in one squeeze (or 50 ml) of the bulb has been achieved after aspirating 900 ml. The CO concentration in the duct air is given by:

$$\frac{50}{900} \times 0.1\% \times 10{,}350\ \text{ppm} \times 1145\ \mu\text{g}\cdot\text{m}^{-3} = 65{,}837\ \mu\text{g}\cdot\text{m}^{-3}$$

where

10,350 ppm = 1% CO
1145 $\mu g \cdot m^{-3}$ = 1 ppm CO

Knowing the duct gas rate of flow (= duct gas velocity × cross-sectional area of the duct), the mass of CO emitted can be calculated. This, when divided by the fuel consumed in unit time, yields the emission factor.

SICK BUILDING SYNDROME: REVIEW AND EXPLORATION OF CAUSATION HYPOTHESES AND CONTROL METHODS

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ABSTRACT

Control and abatement of indoor air quality (IAQ) problems are dependent upon reliable investigation and diagnosis. Sick building syndrome (SBS), building-related illness (BRI), and other health and comfort problems are selectively reviewed and discussed. Psychological and social as well as physical, chemical, and biological factors that affect occupant physiological and health responses are identified.

Confusion exists regarding definitions and attributes of problem buildings. Timely, comprehensive, systematic investigations are rare, expensive, and difficult. Systematic and other biases result in inadequate investigations and incomplete or incorrect diagnoses. Building ecology and building diagnostics are described as a comprehensive framework for understanding and investigating indoor air quality problems.

Hypothesized causes of SBS are identified based on published SBS and BRI investigation reports and review articles. Methods to control SBS, BRI, and other building-associated illnesses are presented and discussed. Preventive measures to control IAQ-related health and comfort problems and recommendations for further research are given.

INTRODUCTION

Sick building syndrome (SBS) may affect as many as 20% of the office workers in the United States. In a survey of U.S. office workers, symptoms associated by respondents with poor air quality included a tired, sleepy feeling (56%); a congested nose (45%); eye irritations (41%); difficulty in breathing (40%); and headaches (39%) (Woods 1987). Efforts to control and abate the causes of SBS in buildings are potentially important to the economy and to public health. The present paper is a review of selected published reports related to SBS and a discussion of some of the problems limiting our understanding of it.

The complexity of modern buildings presents significant unmet challenges to designers, operators, and investigators. Problems other than air quality can cause or exacerbate the symptoms of sick building syndrome. Psychological and social as well as physical and biological factors interact to create occupant physiological and health responses to building environments. Yet detailed, comprehensive investigations of building-associated outbreaks are infrequent due to the resources and personnel required to conduct them.

Control and abatement of SBS is dependent upon knowledge developed through reliable investigations and diagnoses. Understanding the potential causes of SBS is essential to such investigations and diagnoses. No clear understanding of SBS and no consistent definition of SBS is used. Authorities in the field use differing definitions or confusing terms which impede progress in understanding the phenomenon. In fact,

TABLE 1

Common Features of Symptoms Reported in Cases of Sick Building Syndrome (WHO 1983).

Eye, Nose and Throat Irritation
Sensation of Dry Mucous Membranes and Skin
Erythema
Mental Fatigue
Headaches, High Frequency of Airway Infections and Cough
Hoarseness, Wheezing, Itching and Unspecific Hypersensitivity
Nausea, Dizziness

TABLE 2

Mølhave's classification scheme for symptoms related to sick building syndrome and examples of each (Mølhave 1987).

1. Sensoric irritation in eye, nose or throat
dryness
stinging, smarting, irritating sensation
hoarseness, changed voice
2. Skin irritation
reddening of skin
stinging, smarting, itching sensation
dry skin
3. Neurotoxic symptoms
mental fatigue
reduced memory
lethargy, drowsiness
reduced power of concentration
reduced memory
headache
dizziness, intoxication
nausea
tiredness
4. Unspecific hyperreactions
running nose and eyes
asthma-like symptoms in non asthmatic persons
respiratory sounds
5. Odor and taste complaints
changed sensitivity
unpleasant odor or taste

TABLE 3

WHO classification scheme for symptoms found in sick buildings (WHO 1986).

1. Sensory irritation of skin and upper airways, along with headache and abnormal taste
2. Odor
3. General symptoms such as fatigue, dizziness and nausea
4. Lower airway and gastrointestinal symptoms (*)

(*)Not generally found in sick building syndrome

he most widely accepted definition of SBS requires the absence of identified causes, but even those who present this definition fail to use it consistently.

Knowledge and understanding of SBS is obtained through four primary means: (1) *investigations* of problem or complaint buildings, with or without non-complaint control buildings; (2) multiple building *studies*, which may or may not include complaint buildings; (3) controlled *experiments* in buildings or laboratories where environmental factors are manipulated and the responses of occupants are surveyed; and (4) *literature reviews* where data or findings from various investigations or studies or both are collected and analyzed. The investigations are usually commissioned by building owners, operators, or occupants while the studies and research are usually funded by public or private research or by governmental agencies. Reviews (including the present paper) are usually initiated by interested authors.

DEFINITIONS OF SBS AND OTHER BUILDING-ASSOCIATED ILLNESSES

SBS is variously defined by its symptoms, by its hypothesized causes, or by the demonstration of a statistically valid association of SBS symptoms with a particular building.

Symptoms

SBS is frequently defined by the occurrence of reported symptoms from a group of symptoms listed in several authoritative publications. Most of these definitions declare that the symptoms abate upon leaving the building and worsen upon re-entry (NAS 1981; WHO 1983; Stolwijk 1984; Fanger 1987; Finnegan et al. 1984; Mølhave 1987; Woods 1987). A widely cited World Health Organization report (WHO 1983) lists a broad spectrum of symptoms reported primarily in Scandinavia and the United States. Those symptoms have many features in common and are listed in Table 1.

Mølhave (1987) has proposed a classification scheme for the major symptoms of SBS (Table 2). A World Health Organization Working Group on Indoor Air Quality Research (WHO 1986) has proposed a classification scheme for "sick" buildings (Table 3). These two authorities have presented conflicting schemes. Their lists are inconsistent, and Molhave has classified SBS symptoms while the WHO has classified "symptoms found in sick buildings." The WHO list includes symptoms which it states are not found in sick building syndrome, so a sick building is not equated exactly but overlaps with one in which sick building syndrome occurs.

Causal Factors

Commonly, several broad classes of factors are considered potentially related to an elevated incidence of reported symptoms when a problem is termed SBS (Skov and Valbjorn 1987; Mølhave 1987). These factors include chemical (Mølhave et al. 1984), physical (Alsbirk 1983), biological (Morey 1984), and psychosocial factors (Colligan 1981; Alexander and Fedoruk 1986).

Many authors state that most investigations of SBS have not resulted in definitive identification of causal factors. In fact, most definitions of SBS require that the reported symptoms not be associated with specific environmental or other causal agents. Other definitions of SBS expressly require that the causal agent(s) not be clearly identified or demonstrated by the investigation. Generally, where a causal agent is identified, the symptoms are no longer considered "sick building syndrome"; rather, the building problem is specified as contamination by the causative agent and the illness is termed building-related illness (see discussion below). But confusion exists because many investigators still apply the term SBS to cases where symptom etiology is clearly identified.

Elevated Rate of Symptom Reports

Some definitions of SBS require the demonstrated presence of excess reported symptoms in the complaint building compared with a control building or some other comparable baseline. This involves surveys of building occupants, usually using epidemiologic techniques. However, the measurements made in most reported studies are insufficient to enable identification of the pollutant concentrations and their associations with symptoms. There are usually too few measurements of environmental factors. Large occupant populations are studied through questionnaire surveys, either self-administered or administered by the investigators. The large expense of comprehensive pollutant measurements in each distinct environmental niche within a study building results in few samples of few pollutants in nearly all investigations. Large spatial and temporal variability of indoor air pollutant concentrations within a single building or even spaces within the building (for CO_2, RSP, and VOC, for example) reduce the likelihood that one or a small number of measurements will provide adequate information to identify associations between exposures and symptoms. The "limitations of investigations" are explored later in this paper.

Under the elevated symptom prevalence definition, one or even a small percentage of a building's occupants cannot suffer from sick building syndrome regardless of the symptoms or the building-relatedness of their onset and recurrence.

Sources of Confusion About Terminology

There are two sources for much of the confusion. One involves definitional differences; the other involves inconsistent use of terms. Where the etiology of symptoms and complaints is identified, most investigators do not label the symptoms or complaints SBS or the building "sick" (WHO 1983; Mølhave 1987; Woods 1987). Rather, they define the symptoms as manifestations of illness and classify it as building-related illness (BRI) to distinguish it from SBS. BRI includes such medical conditions as hypersensitivity pneumonitis, Pontiac fever, and allergic dermatitis (Hodgson 1986; Woods 1987). Building-related illnesses are attributed to a broad range of pollutants including infectious microorganisms, allergens, chemicals, moisture, temperature, noise, vibration, and poor illumination.

Building-Associated Epidemics

Kreiss and Hodgson have used the term "building-associated epidemics" to include both SBS and BRI (Kreiss and Hodgson 1984).

Other authors have used BRI as the all-inclusive term covering two categories of episodes: "those characterized by a generally uniform clinical picture for which a specific etiology can often be identified, and those in which affected workers report nonspecific symptoms temporally related to work" (Samet et al. 1988).

While asserting that SBS does not involve identified etiology, some authors still label cases as SBS which include bacterial diseases (such as Legionnaire's disease and Pontiac fever), thermal discomfort, and irritation caused by chemicals, and they call such buildings examples of "sick" buildings

(WHO 1986; Berglund and Lindvall 1987). Thus, confusion is caused by the overlapping but different use of the terms "sick building" and "SBS."

Some authorities argue that buildings cannot be "sick," they may only be contaminated. The term "sick building syndrome" may just inappropriately medicalize an engineering, architectural, or maintenance problem (Hodgson 1989).

Sick Buildings

In listing types of "sick buildings," Berglund and Lindvall (1986) include buildings contaminated with radon, molds, contagious agents, and formaldehyde, and they add to the list "buildings in which the occupants show reactions and symptoms similar to those known to be caused by formaldehyde (Andersen et al. 1975) but in which the concentrations of formaldehyde are well below known reaction thresholds." Berglund and Lindvall appear to focus on defining "sick" buildings rather than the symptoms of the occupants, as in SBS. Recently, Berglund and Lindvall have promoted the use of the term "healthy buildings" through the convening of an international symposium on the subject (Berglund and Lindvall 1988).

Alexander and Fedoruk (1986) have categorized the particular type of problem building added by Berglund and Lindvall as "epidemic psychogenic illness" or "mass hysteria." According to Alexander and Fedoruk, the terms are interchangeable but the first is preferred due to the tendency to misunderstand the second. Like many investigations of sick building syndrome, the diagnosis of mass psychogenic illness is difficult to document and strongly resisted by the affected building occupants (Alexander and Fedoruk 1986).

An example of mislabeling is a recently reported investigation of "tight building syndrome," or "closed building problem," and "new building problem." The authors described the case as fitting the WHO (1983) SBS definition including the usual symptoms and the failure to identify the causative agent(s) (Whorton et al. 1987). When an extended summary of the Whorton article was prepared by others later, the case was termed an investigation of an outbreak of "building-related illness" (HESIS 1987).

Building-Related Illness

Many authors explicitly distinguish SBS from building-related illness (BRI), which includes allergic respiratory disease (sinusitis, tracheobronchitis, asthma, hypersensitivity pneumonitis, and humidifier fever), skin diseases (irritant, allergic, and photodermatitis), irritant syndromes (carpet shampoo, formaldehyde), and infections (Legionnaire's disease, Pontiac fever, Q fever) (Kreiss and Hodgson 1984; Hodgson and Kreiss 1986; Stolwijk 1984; Woods 1987; Mølhave 1987).

Building Sickness

The term "building sickness" was proposed in 1984. Lars Mølhave of Denmark suggested the term "building sickness" to characterize reported symptoms in a building in which "the occupants report comfort or health problems which they assign to the indoor atmospheric environment." Mølhave would limit the use of the term "sick building" to cases in which the problem is identified as multifactorial and in which no measured factor exceeds generally accepted thresholds or recommendations (Mølhave 1987). This is similar to most definitions of SBS without the criterion that there be a statistically significant excess of reported SBS complaints and symptoms.

It is possible that the term "building sickness" has not received more use due to the alternate meanings of the initials BS—British Smoke, which is used in epidemiologic studies involving particulate matter, and a vulgar American slang expression.

TABLE 4

Proposed classification scheme for occupant condition in problem buildings (after Woods 1988).

1. Unresolved.
   Symptoms reported or complaint rates deemed unacceptable by owners, operators or occupants but do not meet standard statistical tests to confirm their association with occupancy of the building. This can occur where contamination or complaints are limited to a small area of a building or occur among the general building population but at rates similar to those found in buildings in general.
2. Building-associated illness.
   Complaint or symptom rates are elevated compared to control buildings or numbers derived from large population studies. Investigation confirms that the complaints are related to occupancy of the building.
   a) Sick building syndrome (SBS) or building sickness (BS). Symptoms are similar to those identified in Tables 1 and 2, but no specific cause of the complaints can be demonstrated by the investigators.
   b) Building-related illness (BRI).
      The disease entity is medically identified and verified. Contamination problems determined as directly associated with the disease(s) involve a wide range of agents and factors including infectious microorganisms, allergens, chemicals, moisture, temperature, noise, vibration and illumination.
   c) Unclassified building associated illness.
3. Undetected problem buildings.

TABLE 5

Causal factors identified in investigations of SBS (after Wallace 1988).

MULTIFACTORIAL
Sex
Hay fever
Migraine
Smoking
Home-related illness
Carbonless copy paper use
Xeroxing > 25 sheets/d
VDT use > 1 h/d
Unsatisfied with job
PHYSICAL FACTORS
Ventilation
Ions
Other physical causes
CHEMICAL FACTORS
Formaldehyde
Other volatile organic chemicals
Semivolatile organic chemicals
BIOLOGICAL FACTORS
Molds
Bacteria
Allergens

Etiology of Confusion

Mølhave suggests that the different or inconsistent use of terminology results from the involvement of different groups of "indoor climate experts." For example, the term "irritation" is used by medical experts as a synonym for toxic skin damages known from occupational exposures; by technical and engineering experts to describe acceptability or unacceptability of the indoor environment; and by the occupants to describe subjective feelings of reduced comfort due to dry nose, dry eyes, and dryness or stuffiness of the air (Mølhave 1987). Thus, the backgrounds of the investigators may significantly impact the diagnoses.

Working Assumptions

In the remainder of this paper, the definitions and concepts articulated by the WHO Working Group (WHO 1983), Stolwijk (1984), Mølhave (1987), and Woods (1987) are relied upon as the basis for the discussion. These exclude building-related illness and emphasize multifactorial sick building syndrome.

Classification of the occupants' conditions in problem buildings will be classified according to a scheme adapted from that proposed by Woods as follows: 1) unresolved building-related complaints or symptoms; and 2) building-associated illness including a) building sickness, b) building-related illness, and c) unclassified building-associated illness. Woods has also added the category "undetected problem buildings" which will not be discussed further here (Woods 1988). See Table 4 for definitions of each of these categories.

FINDINGS FROM MAJOR STUDIES

Potential Etiologic Agents of SBS from Recent Studies

Wallace has reviewed the recent literature on SBS (1988). The review covers published reports from 1984 through 1987. The results of his review are presented in Table 5. Five causal factor categories were developed: physical, chemical, biological, psychological, and multifactorial. Wallace did not review research on psychological factors.

The causal factors hypothesized cover a wide range and the study methods also were diverse. Wallace drew no conclusions from the literature, but his presentation is interesting for the range of factors considered and the amount of interest in SBS represented by the reviewed work.

Several major multi-building, multi-disciplinary studies have been reported, four in Great Britain (Finnegan et al. 1984; Pickering et al. 1985; Harrison et al. 1987; Hedge et al. 1987) and one in Denmark (Skov and Valbjorn 1987). They have developed conflicting conclusions about SBS causal factors.

Two British studies found higher symptom prevalence rates in mechanically ventilated buildings than in naturally ventilated ones (Finnegan 1984; Harrison 1987). Among the mechanically ventilated buildings in the later study, those with humidification had the highest symptom rates. However, among 11 naturally ventilated buildings were two in which symptom prevalence rates were typical of the 16 sealed buildings in the study (Harrison et al. 1987).

Finnegan reported a threefold excess of SBS symptom prevalence rates in five mechanically ventilated buildings (15%–45%) compared with three naturally ventilated buildings (5%–15%) (Finnegan and Pickering 1987). There was a noticeably wide range of building-specific symptom prevalence rates (5%–45%) in buildings characterized by the authors as non-complaint buildings. Incomplete evaluation of building system performance or operation through either inspection, analysis, or environmental measurements has been reported by these authors. No reported measurements have been published.

Another large-scale British study of 30 buildings found "few differences in symptom prevalence" between naturally and mechanically ventilated buildings. (The definition of mechanical ventilation here was "a ducted system but with no plant for heating and cooling.") Higher symptom prevalence rates were found for all symptoms in air-conditioned than in non-air-conditioned buildings and for females than for males. A higher prevalence was found for all symptoms and all ventilation system types in the public sector than in private-sector buildings (Hedge 1987). The published report does not detail the inter-building variations in prevalence rates.

The Danish investigators found no correlation between complaints and building ventilation type. They found a number of factors associated with elevated symptom prevalence including age of building, sex of occupant, job category, type of work, temperature, number of occupants, amount of open shelving, and what they called the amount of "fleecy material" (Skov and Valbjorn 1987). These findings are discussed in greater detail below.

"Multifactorial Sick Building Syndrome"

Several investigators have suggested that the etiologic agents in SBS were multiple factors, none of which alone causes increased symptoms and complaints (Turiel et al. 1983; Mølhave 1987; Woods 1988; Valbjorn and Skov 1987). In fact, measurement of a broad spectrum of environmental parameters usually fails to isolate particular agents as etiologic. Multifactorial analysis identifies clusters of factors associated with higher rates of reported symptoms (Valbjorn and Skov 1987).

The Danish Town Hall Study

The most comprehensive SBS study reported to date is a multifactorial investigation known as the Danish Town Hall Study (DTHS). Covering a total of 27 buildings that were not known problem buildings, the DTHS involved measurements of indoor climate and other environmental parameters in 14 town halls. A questionnaire and clinical study of 4369 employees in the town halls and 13 affiliated buildings was also conducted. While reported symptom levels were high for mucosal irritation (28%) and for general symptoms in the form of headache, abnormal fatigue, or malaise (36%), the measurements of environmental parameters did not result in elucidation of the epidemiology.

However, the differences in the prevalence of symptoms among buildings was significant and was correlated with building factors as well as occupant factors. Building factors that could explain the difference in the prevalence of symptoms included the total weight and potentially allergenic fraction of floor dust, the area of "fleecy" material per cubic meter of air, the length of open shelves per cubic meter of air, the number of work stations, and the air temperature. Occupant factors included sex, type of work, and job category. See Table 6 for the results of the environmental measurements (Valbjorn and Skov 1987).

Among the findings were the following:

1. Elevated rates of reported mucosal irritation were associated with the size of the allergenic fraction of floor dust, the length of open shelves per cubic meter of air, the area of fleecy material per cubic meter of air, the number of work stations, and air temperature.

TABLE 6

Indoor climate measurements in 14 Danish town halls (Valbjorn and Skov 1987).

	Units	Mean	Range Low	Range High
Mean external temperature	(24 hours)(°C)	2.4	−1.2	11.4
Average daily sunshine	(hours)	2.3	0	6.4
Air temperature	(°C)	22.7	20.5	24.1
Person-weighted air temperature	(°C)	23.0	22.0	24.4
Temperature rise during a work day	(°C)	2.5	1.0	8.0
Vertical temperature gradient	(°C/m)	0.9	0.4	2.0
Air velocity	(m/s)	0.15	<0.15	0.20
Relative humidity	(%)	32	25	40
CO_2	(%)	0.08	0.05	0.13
Formaldehyde	mg/m^3	0.04	0	0.08
Static Electricity: Observer	(kv)	1.4	0	4.8
Occupants max.	(kv)	1.7	0	4.0
Airborne dust	(mg/m^3)	0.201	0.086	0.382
Dust particles: > 0.5 um	(l^{-1})	48×10^3	19×10^3	119×10^3
> 2.0 um	(l^{-1})	25×10^2	8×10^2	116×10^2
Airborne microfungi	(col/m^3)	32	0	111
Airborne bacteria	(col/m^3)	574	120	2100
Airborne actinomycetes	(col/m^3)	4	0	15
Vacuum cleaned dust[a]	$(g/12m^2)$	3.67	0.32	11.56
Vacuum cleaned dust[b]	$(g/12m^2)$	6.14	0.66	17.04
Macromolecular content in the dust	(mg/g)	1.53	0	5.24
Macrofungi in the dust[a]	(col/30mg)	33	11	90
Macrofungi in the dust[b]	(col/30mg)	32	6	192
Bacteria in the dust[a]	(col/30mg)	199	41	380
Bacteria in the dust[b]	(col/30mg)	296	160	680
Man-made mineral fibers in air MMMF	(f/m^3)	5	0	60
Not MMMF (< 3 um) in the air	$(f \times 10^3/m^3)$[c]	33.2	18.5	59.1
Not MMMF (> 3 um) in the air	$(f \times 10^3/m^3)$[d]	3.1	0.7	5.0
Volatile Organic Compounds (charcoal)	(mg/m^3)	1.56	0.43	2.63
Volatile Organic Compounds (Tenax)	(mg/m^3)	0.5	0.1	1.2
A-weighted equivalent background noise, $L_{a,eq}$	(dB)	56.7	51.3	60.3
A-weighted equivalent background noise, L_{95}	(dB)	36.2	28.2	44.1
Reverberation time	(s)	0.41	0.28	1.05

[a] = In the office where all the measurements were performed
[b] = In an office with a considerable loading of clients during the day.
[c] = Mean readings in 6 buildings
[d] = Mean readings in 13 buildings, in one building measured 32 mg/m^3

2. Symptoms correlated strongly with job category. The symptom prevalence varied highly with job category, and the highest prevalence was found in the subordinate job categories. Jobs involving photoprinting, working at video display terminals, and handling carbonless paper correlated with the reported frequency of mucosal irritation and of general symptoms; the number of weekly working hours of women also correlated with reports of these two symptom categories, although less markedly.
3. As in several other studies, women had a higher symptom prevalence rate than men and complained more frequently about indoor climate.
4. Symptom prevalence rates varied significantly among buildings, supporting the notion that the symptoms are building-related. Individual town halls correlated significantly with reported mucosal irritation and general symptoms. The lowest prevalence of symptoms was found in the oldest town halls (buildings were mostly newer than 30 years of age, with one almost 50 and another 80 years old).
5. The difference between mechanically and naturally ventilated buildings was not significant for this study. This is in sharp contrast to the findings on the large-scale British study (Finnegan et al. 1984; Robertson et al. 1985).

The DTHS strongly supports the findings of many investigations that extensive measurement of environmental variables, including air quality, may not reveal "the cause" of the complaints. It appears more likely that a constellation of factors including some combination of those identified above as well as chemical or biological contamination and improper ventilation system design, construction, maintenance, or operation will be found in problem buildings.

POTENTIAL ETIOLOGIC AGENTS IN SBS FROM THE DTHS

We have hypothesized etiologic relations of some potential causal agents/factors identified in the Danish Town Hall Study (see Table 7). In Table 8 we have attempted to identify potentially additive or synergistic co-variables. The following discussion is based on those two tables. The discussion focuses on some environmental and institutional factors frequently associated with increased symptom or complaint rates in problem buildings (Turiel 1983; Mølhave 1987; Valbjorn and Skov 1987; Woods 1987).

VOC as Potential Sources of Complaints

Reporting on an earlier study, Mølhave (1982) identified 42 commonly used building materials and measured their volatile organic compound (VOC) emissions. A total of 52 compounds were identified. An average of 22 compounds was identified from each material, and the range of emission rates

TABLE 7

Building and occupant factors (Valbjorn and Skov 1987) and their possible connection to the etiology of building sickness.

	ENVIRONMENTAL AND OCCUPANT EFFECTS	
FACTORS IDENTIFIED IN DANISH TOWN HALL STUDY	**CO-FACTOR**	**HYPOTHESIZED FACTOR IN SBS ETIOLOGY**
1. TEMPERATURE (elevated)	Microorganism proliferation	Bioaerosol increase
	Higher VOC emissions/air levels	VOC increase
	Reduced airflow	Contaminant increase
	Reduced ventilation	Increased contaminant levels
2. FLEECY MATERIAL	More VOC sources	Increased VOC levels
	More VOC adsorption surface area	Increased VOC levels
	More fiber sources	Increased airborne fibers
	Difficult housekeeping	Increased airborne dust
3. OPEN SHELVES	More adsorption sites	Increased VOC
	Fine particle deposition sites	Increased airborne particles
	More difficult housekeeping	Increased particles, VOC, bioaerosols
	More source surface area	
4. NEWER BUILDINGS < 30 years	More fleecy surfaces	VOC, particles, aerosols
	Fewer private offices	Noise, crowding, contaminant levels
	Higher occupant density	Increased exposure to contaminants
	Less occupant control	Decreased resistance to illness
5. JOB CATEGORY	Less mobility during day	Increases exposure to contaminants
	Less control over time/work	Personal stress, reduced resistance
	Lower status	Higher exposure, less ventilation
	Less control over work area	Increased stress, reduced resistance
6. TYPE OF WORK	More exposure to toxins	More physiological stress
	More exposure to irritants	More physical and mental stress
	Stressful work posture	More physical stress
7. OCCUPANT DENSITY	Lack of privacy	Psychological stress
	Inadequate ventilation	Increased contaminant levels, exposure
	More local pollutant sources	Increased contaminant levels, exposure
8. #/WORK STATIONS	Anonymity, impersonal environment	Psychological stress
	Lack of privacy, control	Psychological stress
	More local pollutant sources	Increased exposure

was extremely large. The arithmetic average emission rate was 9.5 mg/m²h. Three model rooms constructed from the materials were found to contain between 23 and 32 of the compounds at concentrations from 1.6 to 23.6 mg/m³. When the cancer risks and health effects (Mølhave classifies irritation as a health effect) of each of the 52 compounds were reviewed, 82% were known or suspected mucous membrane irritants and 25% were suspected or known animal carcinogens.

A very high percentage of common VOC emitted from building materials are known or suspected mucous membrane irritants; therefore, it is reasonable to expect significant numbers of building occupants to experience mucous membrane symptoms in newly constructed, remodeled, or furnished buildings. Turiel et al. (1981) suggested that a number of contaminants acting synergistically may have been responsible for the higher symptom incidence in a comprehensively investigated problem building.

Hollowell (1981) suggested that the reason building occupants complained about what they ought not to be able to perceive (VOC) at the very low measured airborne concentrations was that the composite effect might give rise to the reported health effects. Others have supported that theory (Mølhave 1982; Stolwijk 1984).

Noma et al. (1988) have found correlations between VOC profiles and their distribution patterns in one "sick" and one "healthy" Swedish preschool of identical design. Using sophisticated statistical analyses, they examined the patterns of VOC distribution in various locations in the two buildings. They concluded that the distribution of VOC was more uniform in the healthy than in the sick preschool.

Thermal Factors

Elevated temperature in a building can have many effects on the building environment and directly or indirectly on the occupants. Not the least among them is discomfort from the temperature itself. This discomfort can reduce tolerance to other factors, many of which may be exaggerated by the elevated temperature. Additionally, microorganism growth may be enhanced, VOC emissions from materials will increase, and ventilation airflow will normally decrease.

Microorganism Contamination. Biological aerosol concentrations might increase due to increased growth and proliferation of microorganisms associated with higher temperatures, reduced outside airflow, and increased demand on air-conditioning equipment. Some organisms may proliferate outdoors or on building equipment surfaces in warmer weather. An important example are the Legionella bacteria responsible for Pontiac fever, which has been reported as occurring almost exclusively in spring and summer (Friedman et al. 1987). Many of the reported outbreaks of Legionnaire's disease have also occurred in spring or summer.

VOC Emissions. VOC emissions will increase as a result of the temperature-based increase in vapor pressure. Girman (1987) has calculated that a 13°C rise in temperature will result

TABLE 8

Identification of Possible Synergistic Risk Factors for SBS Based on Risk Factors in Danish Town Hall Study

1. TEMPERATURE + FLEECY MATERIAL + OPEN SHELVES
More organic sources, emissions
More microbiological activity
2. JOB CATEGORY + TYPE OF WORK
Low status = loss of control, mobility, job satisfaction
Reduced proximity to windows – light, views, outside air
Combined stressors of work posture, toxins, irritants
3. NUMBER OF WORK STATIONS + AGE OF BUILDING
Higher density in open office plan, newer buildings
More local sources
Less privacy, control, space
4. SEX + JOB CATEGORY
Females in subordinate (clerical) positions
Type of work (see #2 above)

in a 200% increase in typical VOC vapor pressure. The increase in emissions will be greatest from materials with large surface areas in the air-stream and from materials where the emission process is dominated by evaporation from the surface rather than diffusion from within the material. Some of the materials with large exposed surface areas are freestanding partitions, bottoms of ceiling tiles facing the interior, tops of ceiling panels facing concealed spaces serving as return air plenums, fibrous linings of air ducts, and textiles or fabrics covering walls, furnishings, or floors.

Ventilation Airflow. Many mechanical ventilation systems will reduce airflow and outside air supply to the interior when temperatures rise toward the upper end of the comfort range. This is particularly true of variable-air-volume (VAV) systems. When temperatures are elevated, increased ventilation is most necessary to remove contaminants resulting from higher emission rates and increased airflow is required to provide evaporative cooling of occupants' exposed skin surfaces. Yet, under most ventilation system control designs, airflow or ventilation or both may be reduced.

High Surface Area Interiors

"Fleecy material" and "open shelves" were identified as risk factors in the Danish Town Hall Study. "Fleecy" refers to materials such as fabrics and carpets which have rough, textured surfaces. The association with elevated symptoms might result from the extremely large effective surface areas facing the interior space on fleecy materials or open shelving systems. "Effective" surface area refers to the actual surface area available for adsorption and re-emission sites for VOC or deposition of small particles. Recent advances in mathematics (fractal math) have shown that the actual surface area available for particle deposition or molecular adsorption is many times larger than the two-dimensional (plane geometry) measured surface area. Small particles, which penetrate deepest in the respiratory system, deposit equally efficiently on horizontal and on vertical surfaces (Weschler 1988).

Carpets, textiles used for wall coverings and furnishings, and insulation materials facing the interior or the airstream in mechanical ventilation systems are high-surface-area materials that provide more adsorption sites for VOC and more deposition sites for small particles. Fibrous materials also provide readily available source material for airborne particles through surface erosion, abrasion, or deterioration of the binding forces. Housekeeping tasks including cleaning, vacuuming, and dusting are made more difficult by rough surfaces and the larger surface areas, thereby resulting in the presence of a greater reservoir of unattached particles which may become airborne when disturbed by human activity or ventilation airflow.

VOC Emissions. VOC emitted from building materials have been shown to distribute themselves on exposed materials throughout enclosed spaces and then are re-emitted for several weeks or more (Berglund et al. 1987). Many "fleecy" materials (such as carpets, upholstered furnishings, fabric wall coverings, fiberglass insulation, and air ducts) are known sources of VOC. Many carpets and wall coverings are fastened to the floors and walls, respectively, with adhesives that are known sources of VOC. It is apparent that buildings with large surface areas (from both fleecy materials and open shelves) will likely be associated with elevated VOC air concentrations. It is also likely that VOC concentrations in such buildings will decrease more slowly than in buildings with hard or smooth surfaces and less surface exposed to the interior.

Age of Building

A clear association was found in the Danish Town Hall Study between age of building and complaint or symptom rate, with the oldest buildings having the lowest rates. Newer offices are often constructed from softer, less durable materials on the major surfaces—floors, walls, and ceilings. This could result in higher airborne particle concentrations from deterioration of the surfaces or finishes and polishes applied to them. Newer offices are usually planned with some or all "open office planning" rather than predominantly enclosed or private office spaces typical of older offices.

Densities of workers (per unit of area) in open offices are usually higher than in private offices. This results in many environmental problems, including noise; chemical, physical, and biological contamination of air; lack of visual privacy; lack of audial privacy; and lack of control over personal workspace.

Architects usually control open office acoustic problems by using high-surface-area materials and components (open shelves, freestanding partitions) and by utilizing fleecy materials (carpets, fibrous glass ceiling panels or insulation, fabric-covered partitions). This reduces reverberation time and breaks direct paths of sound transmission. The partitions, where used, also provide some visual privacy and a feeling of occupant control (at least over the immediate work station area). However, they do substantially increase surface area and impede space air distribution.

Job Category and Type of Work

Lower status jobs were associated with higher complaint and symptom rates in the DTHS. Subordinate workers, such as clerical and drafting personnel, tend to spend more time at the work stations than their supervisors, who often move about the building or leave it to attend meetings. Lower status workers also tend to have less space and to be located near the interior of the building.

Outside air supply to the interior is usually less than at the perimeter. Some buildings deliver primarily or only recirculated air to the interior spaces. Thus, interior spaces may have stagnant or stale air. The combination of higher density, more activity, and less ventilation would result in higher concentrations of airborne contaminants. Perimeter offices would be more likely to have views out of windows, providing the worker with visual and psychological relief.

Type of Work. Certain jobs involve exposure to chemical and physical agents known to cause irritation, nervous

system effects, and other health outcomes. Equipment and materials used in duplicating, printing, mailing, and clerical activities in general are all associated with various chemical and physical agents which may contaminate indoor air. It is also likely that individuals performing such work will be in subordinate positions and therefore at risk as discussed above.

Occupant Density and Number of Work Stations

It is not clear whether the DTHS found high occupant density associated with higher symptom report rates because of the density or the possible correlation of high density with job category and type of work, as described above. Lower status workers are likely to have less assigned personal work area, i.e., higher occupant density. At higher densities, the occupant-generated air contaminants (metabolic- and activity-based) will be more concentrated prior to dilution or removal by ventilation.

A higher number of work stations might be associated with increased anonymity, a lack of personal privacy and control, and a higher rate of contaminant generation. All of these could affect occupant stress and comfort levels.

Woods (1988) has found a high proportion of buildings with high occupant densities that exceed the design capacities of the ventilation system. Occupants are added without modification to the ventilation system, resulting in inadequate air supply, interruptions of design airflows, and excessive loads on cooling and heating equipment.

LIMITATIONS OF INVESTIGATIONS

There are numerous limitations on investigations of problem buildings which suggest explanations for the frequent failure to identify etiologic agents or contributory building factors. Among these limitations are cost, timeliness, investigatory methods, building complexity, building dynamics, institutional constraints, and insufficient guidance to investigators.

Unsystematic and incomplete investigations result in inadequate diagnoses and unsuccessful remedial efforts. Yet complete, systematic investigations are rare. Expert investigators are usually selected by the occupants or building owner according to the owner's perceptions of the problem etiology. Expertise is usually confined to one or a limited number of fields, resulting in incomplete investigations and narrowly focused findings in many (Mølhave 1987; Kreiss and Hodgson 1984).

The perseverance of the investigators and the availability of methods can determine whether chemical and biological agents can be eliminated as etiologies of building-associated outbreaks (Kreiss and Hodgson 1984). In many instances, ventilation system problems are identified early in the investigation. Modifications to the system equipment, operating schedule, or operational modes (airflow, temperature) will result in a significant reduction of complaints and symptoms, and the investigation will be terminated before problem causes are defined.

Timely investigations rarely occur due to institutional constraints. Frequently, when complaints or symptoms are initially reported, there is hesitation by management to give importance to them. It is often only when complaints become very numerous, when upper-level management personnel are affected, or when workers initiate organized or formal action that management commissions investigators.

Comprehensive and systematic investigations are expensive, difficult, and more time-consuming than building operators or users can normally tolerate. In many cases it is not considered necessary and it is not economically feasible to identify causes if remedial measures can effectively reduce complaints and symptoms, as in the case of ventilation system modifications. Thorough characterization of environmental factors, including detailed chemical and biological contaminant measurements, can be prohibitively expensive and is only undertaken in the most severe or persistent of cases.

Protocols to guide investigations of problem buildings have not been widely tested, validated, or promulgated by any standards development organization. While some generalized protocols have been prepared, significant differences among problem building cases require individualization of protocols and measurement methods (Levin 1987c; NAS 1985; NIOSH 1987; Sterling et al. 1987; Woods et al. 1988). A standard guide for investigation of problem buildings is currently being prepared by the ASTM (Levin 1988).

Standardized sampling and analytical methods for indoor air are limited and those that exist are not uniformly applied or widely used. Efforts to address these shortcomings are under way by the ASTM (Levin 1988). However, interbuilding variations limit standardization of investigations and comparability of results (Levin 1987c).

Comprehensive monitoring for airborne contaminants is extremely expensive and rarely definitive in problem building investigations. Monitoring for airborne VOC is expensive and there is a lack of general agreement regarding appropriate monitoring methods. Characterization of total VOC is not as expensive as identification and quantification of specific compounds, although the methodological problems are significant.

Even where extensive environmental monitoring is conducted, interpretation of results is limited by the absence of guidelines and standards. Interpretation is often based upon standards or guidelines developed in and for different contexts, such as the industrial workplace and ambient air. Comparison of measurements to such guidelines or standards can lead to incorrect assumptions about the effect of the measured parameter on occupant health and comfort (Eisinger 1988).

Limitations Imposed by the Problem Context

Buildings are dynamic, responding to changes in the external environment, internal loads, and the building itself. Internal loads may be generated by user activities, building equipment, or occupants' appliances and equipment. Building loads vary as a result of normal operation of building equipment, principally lighting, ventilation, heating, and cooling. Malfunctions in building equipment, interventions by occupants, manipulation by building operators, and signals from building systems controls constantly effect changes in equipment operation, resulting in load changes and load handling.

Environmental variations among locations within a single building can be enormous. Small distances between locations can involve large differences in some environmental variables including critical air quality factors. Significant variations in environmental factors occur hourly, daily, and seasonally. Therefore, monitoring of environmental factors, including but not limited to the sampling and analysis of indoor air, can produce misleading results unless an adequate number of representative samples is collected over extended or adequately representative time periods and locations. This may be an especially important factor in the failure of many large building or multi-building studies where associations between reported symptoms and environmental variables are not found at statistically significant levels. Single-area measure-

ments or one measurement per floor or per ventilation system for many occupants will simply average precisely the variations that the study seeks to elucidate.

Designer, operator, and occupant perceptions frequently differ from each other and from actual building conditions. Investigator interviews with some but not all of these parties can result in biased assumptions or hypotheses followed by incomplete or poorly focused investigations.

DISCUSSION OF SICK BUILDING DIAGNOSES AND FINDINGS

By definition, an SBS diagnosis requires confirmation that an elevated complaint or symptom rate is associated with occupancy of a particular building, that no known etiology accounts for the symptoms, and that clinical evidence of building-related illness is absent.

SBS can be hypothesized but not diagnosed or defined based solely on clinical evidence unless sufficient numbers of occupants are examined in the case building and compared to occupants of a control building or to a valid baseline for symptom prevalence. Clinical identification of symptoms associated with occupancy of a particular building can result in an SBS hypothesis. Only an epidemiologic or clinical investigation can define the occurrence of SBS. Even where epidemiologic evidence supports an SBS hypothesis, BRI may be present in some or all of the occupants manifesting SBS symptoms.

SBS may involve diverse reactions among building occupants. This may be a function of varying conditions within the building, varying individual responses to environmental factors, or both. Where this is the case, it will reduce statistical associations between reported symptoms and measured environmental conditions, and may lead to incorrect interpretations of even the most complete and careful investigations.

Therefore, as defined and discussed in this paper and elsewhere, SBS may not be a useful term in that it refers to symptom sets which are manifestations of various distinct illnesses or diseases. Aggregating these distinct medical conditions may be the greatest barrier to discovery of the causes of sick building syndrome.

Building Diagnostics

"Building diagnostics" is the name given to a set of practices used to assess the current performance and capability of a building and to predict its likely performance in the future (NAS 1985). While building diagnostics can be valuable at many stages in the life of a building, it may be most useful in investigations of problem buildings. Four elements are essential to building diagnostics, according to the NAS report; they are as follows:

(1) knowledge of what to measure,
(2) availability of appropriate instruments and other measurement tools,
(3) expertise in interpreting the measurements, and
(4) capability of predicting the future condition of the building based on that interpretation.

Several authors have proposed phased investigations of problem buildings or in other applications of building diagnostics (NAS 1985; Sterling et al. 1987; NIOSH 1987; Woods et al. 1988). Woods et al. (1988) have divided the phases as described below.

1. Consultation—scope of the investigation is defined and observations of the building and its systems are made (walkthrough survey). Few or no instrumented measurements are made.

Most advocates of phased diagnostic investigations of problem buildings urge extremely limited use of airborne monitoring during the initial phase. They assert that the majority of building problems can be solved or resolved without extensive monitoring. Furthermore, it is argued that monitoring is of limited effectiveness until it can be focused on hypothesized causal agents or factors.

2. Qualitative diagnostics—hypotheses are formulated through engineering analysis; system performance analysis is initiated with limited measurements (such as airflow and pressure differences). Medical evaluation identifies suspect pollutants and air or bulk samples will be collected for these substances.

3. Quantitative diagnostics—if further investigation is needed to test hypotheses, samples will be collected and analyzed and other environmental measurements will be made.

BUILDING ECOLOGY

Indoor air quality is beginning to receive recognition as an important indoor environmental factor as lighting, acoustics, privacy, security, thermal comfort, and aesthetics have received historically. An approach to understanding buildings and human health based on a systematic, comprehensive framework is badly needed. We recommended an ecological approach—a methodology utilizing knowledge and analytical methods like those used by biological scientists in the study of living organisms in relationship to their environment. We have borrowed from the core of the definition of ecology to coin the term "building ecology," which we define as the study of buildings and their relationship to the natural and built environment around them and to humans who use or are otherwise affected by them (Levin 1981).

We suggest that the concepts of dynamic, interdependent flows used in studying ecosystems exemplify methods that can be adapted to the study of indoor air and human health. An example is a mass balance and mass flow analysis of a contaminant or of moisture into, through, and out of a building. Models for such mass balances and flows have shown that changes in one factor can shift the rate of the processes and the overall distribution of contaminants. Chaos theory in physics has shown that a small perturbation can initiate major deviations from a steady state or regular periodic behavior. Building environmental control systems designed to address these perturbations are themselves subject to changes resulting in small perturbations. There are time constants or lags for each of these changes as well. Thus, the system is an ever-shifting collection of interconnected entities—in the case of the building, both living and inanimate; in the case of the ecosystems, each organism and its environmen.

PREVENTING AND REMEDIATING PROBLEM BUILDINGS

Based on the causal factors identified in the Danish Town Hall Study and other investigations, we have identified some potential preventive or remedial measures to minimize SBS. These measures, which are listed in Table 9, have not been systematically evaluated, but there is considerable evidence to support their potential efficacy in reducing the occurrence of sick building syndrome.

CONCLUSION

Buildings are complex. Their effects on humans are extensive and are poorly understood. Attitudes toward and un-

TABLE 9

Potential Control Measures for Multifactorial SBS

HARD SURFACES
Reduce surface area of materials exposed to interior.
Use building form, layout, and surface treatment for acoustic control.
LOWEST COMFORTABLE AIR TEMPERATURE
Especially when building or furnishings are new or after floor and furniture polishing, waxing.
MINIMIZE OPEN STORAGE SHELVING
Use enclosed shelves where possible.
Locate shelves in separate space with exhaust ventilation, no recirculation.
LOW OCCUPANT DENSITY
Utilize total building space for roughly equal area per occupant. Avoid crowding. Confirm HVAC capacity for additional occupants.
MAXIMIZE OUTDOOR AIR SUPPLY
Extend hours and days of operation; increase percent outside air. Start-up earlier after days of vacancy.
INCREASE WORKER CONTROL, PRIVACY
Provide local and individual control over lighting, ventilation, heating, cooling, acoustic environment.
FLEXIBLE WORK HOURS
Allow individual schedule, where feasible.
MINIMIZE EXPOSURE IN STRESSFUL JOBS
Rotate jobs, mandatory rest (fresh air?) breaks.

derstandings of buildings' effects on occupant health and comfort are not generally shared.

Sick building syndrome is inadequately understood at this time, in part due to confusion in definitions and terminology, in part due to inadequate efforts to study comprehensively its occurrence and causes. Potential causes have been identified and discussed, but the definition of SBS may itself preclude elucidation of its causes due to the limitations on investigations. There are great difficulties inherent in conducting comprehensive investigations or studies that are sufficiently sensitive to detect relevant associations.

Causes of SBS require further investigation. An approach for conceptualizing and conducting problem building investigations has been outlined. We recommend that further efforts to develop and refine models for application in diagnosing problem buildings be developed. Field studies, laboratory studies, and modeling efforts need to be performed to further elucidate the causes and nature of sick building syndrome.

Potential control measures have been identified. Evaluation of the efficacy of potential control measures is warranted due to the large costs involved in their implementation and the risks attendant to their failure.

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Commissioning HVAC Systems

Jerry Wesolowski: Is commissioning practical? Now? Is it a European practice to set aside time for commissioning new buildings?

Hal Levin: According to authorities on ASHRAE's committee developing guidelines for commissioning HVAC systems, it is practical, very cost effective. The senior vice president of a major East Coast office building developer says it costs no more if the responsibilities are delineated in the original contract documents.

John Talbott: At the Healthy Buildings '88 conference in Stockholm, speakers said that one to three months were being set aside in some countries. Some attendees did not view this as practical.

Francis Offerman: In Chicago, some building inspections include checking the outside air supply rate of the buildings.

Can Sound Cause SBS Symptoms?

Marian Heyman: At 7.8 to 8.0 cycles per second, vibration is similar to the rate of vibration of atoms in the human body. It is harder to digest food in a noisy cafeteria. We ought to look at the possible effect of noise/sound on human comfort and health.

James Woods: I agree about the potential for human physiological effects responding to sound/vibration found in buildings. Acoustic, thermal, and chemical factors all cause responses. We have found interaction between sound and other factors.

Gyan Rajhans: More complaints regarding noise come from occupants of open plan office environments.

Charged Particles

Paul Loggerquist: Are there any effects of charged particles in the air?

Gene Tucker: This question needs to be investigated more thoroughly than it has been in the past.

Frank Vaculik: It is difficult to do the scientific work needed. Anecdotally, some individuals claim that their personal health is affected by negative ions. The air accompanying storms or in winds such as the Santa Ana is known to make people anxious. People feel better when they open a window, even if there is no air movement.

Asbestos Ceiling Tiles

John Tiffany: A sizable number of ceiling tiles test positive for asbestos, perhaps 5% to 15%. What are the ethical and legal responsibilities of contractors and their workers before they disturb ceiling tiles to work on HVAC systems or to do other work?

Hal Levin: In 1978, the EPA issued a memo to state school facilities and offices informing them that EPA test results showed that 10% to 15% of ceiling tiles tested had asbestos in them.

Richard Shaugnessy: Aggressive sampling for bioaerosols such as that suggested by Phil Morey raises questions about possible disturbance of asbestos-containing materials. Precautions are warranted.

Phil Morey: We are more concerned about fiberglass than asbestos. Workers carry personal protection with them when they go into buildings. There are usually loose fibers in the concealed spaces.

Comfort vs. Health—Do We Need Two Sets of Standards?

Ed Light: I sense a mix of issues between occupant satisfaction, comfort, and health concerns with respect to indoor air quality. Should we have primary and secondary standards as we do for outdoor air? In practice, building managers cannot always protect occupants as much as they would like. The standards would help them do more.

David Grimsrud: The problem with SBS studies is that they look at irritation and not at chronic, non-perceived hazards such as radon and asbestos. I see a trend toward perception of IAQ as a subject in this conference rather than toward objective measures. These are hard to do.

New Standard 62 contains a heroic statement that when strong sources are present, something must be done to control them. Maybe the next generation standard will do it, 5 to 10 years down the road. That's a direction things might go.

Gene Tucker: I have some observations and concerns. In the private sector, manufacturers are now looking not only at perceived effects but also at chronic effects and cancer. We need to be concerned with unperceived effects.

John Talbott: The primary and secondary standards idea is a good one. Primary standards will be developed for carbon monoxide and radon through regulatory processes. Secondary standards issues will be looked at by our conferences.

James Woods: I am concerned about separating health and comfort. In outdoor air, standards are to protect public health. In indoor air, we are concerned with personal health. Would you accept a minimum standard building? We have to live in the buildings we design and build. I start with the World Health Organization definition of health. That leads me to the conclusion that primary standards should be based on comfort, not just on what has been distinguished from health as comfort.

Jerry Wesolowski: I differentiate between comfort and health effects. We should avoid the use of the word "standards"; that means regulation. If we use the word "guidelines," we will have a far more rational dialogue.

Francis Offerman: Building owners financially don't care for the health of occupants. I like the idea of primary and secondary standards.

Dave Grumman: You need to be very careful around ASHRAE with the terms "guidelines" and "standards."

Larry Holcomb: I am interested in risk assessment. Primary standards from outdoors can be extrapolated

into indoor air. Anybody with a PC can do risk assessment with the EPA method.

This means that we will go to low ppb levels. This is easy with water but not with indoor air. Exposure is everyday to lots of low-level indoor air contaminants that cannot be controlled. We need very sophisticated measuring devices. Vinyl chloride levels must not exceed 1 ppb to achieve a 1 x 10^6 risk. Trichloroethylene would be about 5 to 10 ppb for the same risk. These chemicals are ubiquitous in the environment.

Mike Berry: Primary standards might include some things we know enough about. Radon is an example—a great percentage of the public is exposed to radon. Formaldehyde is another—we can act to manage formaldehyde exposures. ETS is another—we have already done a lot with it; millions of people are exposed to ETS.

Asthmatics number about 12 million people in the United States. Probable sources include biocontaminants.
I am concerned about the questions raised by the library study we heard about this morning. What are we doing to control that kind of exposure?

My question to the audience here is this: What are we doing to control moisture in buildings?

Phil Morey: We know more about bioaerosols than we did. The question now is how big a risk do they present? What is their effect on people?

We know we can control mites by reducing moisture levels. We know more about control measures than we do about the effects on people. Standard 62 took a big step by requiring cleanable drain pans. The challenge is to keep humidity levels down downstream from the cooling coils.

John Talbott: I suggest we have primary standards, secondary guidelines.

Ed Light: The library was in a school. The HVAC was off during the summer. Moisture built up. Roof leaks resulted in moisture entry. Relative humidity was 80% when we started the project, 40% to 50% when we finished.

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