Indoor Air Quality Update™

A Guide to the Practical Control of Indoor Air Problems, from Cutter Information Corp.

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Carpet Emissions and Indoor Air

Newly installed carpeting emits volatile organic compounds, often resulting in occupant complaints of odor, irritation, and illness. Investigators blame the problems variously on the carpet, backing, pads, and adhesives.

Clearly, not all carpets are identical. Yet researchers have performed only a small amount of carpet product testing, and very little of it has been published. So what is an architect or facilities manager to do? In this article we explore some recent events, research, and ideas related to cleaning up carpets and improving indoor air quality.

In This Issue

4-phenylcyclohexene (4-PC)

An incident at the Washington headquarters of the U.S. Environmental Protection Agency in early 1988 focused attention on 4-PC, an odoriferous compound associated with the latex backing of many carpet products. 4-PC is apparently formed during the manufacturing of the backing rather than being a constituent chemical of carpet.

In early 1988, employees at EPA headquarters in the Waterside Mall were discovering 4-PC with their noses. Many employees complained of odor and SBS symptoms after new carpeting was installed in part of their building. While the building had been plagued with indoor air quality complaints for years, the carpet incident and the employees' reactions to it brought national media attention to the building and the carpet problem. Employees picketed in front of the EPA building to protest the air quality problems.

The national media coverage of this event boosted public awareness of the carpet problem and of indoor air quality in general. EPA has since relocated a handful of employees to leased space outside Waterside Mall. Many of them believe they have acute chemical sensitivities caused by exposures in the Waterside Mall. Another incident at the building in September 1989 resulted in evacuation of half the employees. Paint fumes from the roof entered the building through an air-handling unit and caused widespread complaints.

EPA conducted a study of its facilities in Washington earlier this year. It has just released the first of three reports on the study (discussed in another article in this issue of ***IAQU***). One source inside EPA close to the study speculated that EPA Assistant Administrator Charles Grizzle would order a major section of the facility evacuated until the environmental problems there could be corrected.

Testing of the building air and of carpet samples at EPA's laboratory confirmed that the offending "new carpet odor" was indeed 4-PC. EPA removed the carpet and eventually sought to install carpeting which did not emit 4-PC. In the process, EPA investigators developed some emissions rate data for 4-PC and other valuable information about the effects of ventilation rates and of airing out carpet prior to installation.

EPA Test Results

Based on the results of chamber testing (without considering possible sink effects in an actual building), the researchers calculated the effects of different ventilation

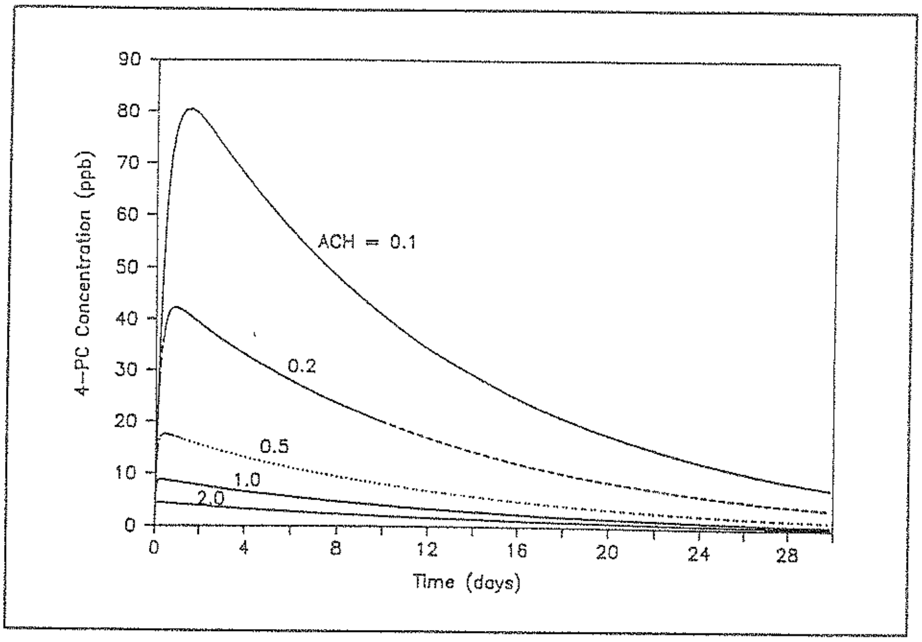

Figure 1 — Effect of Air Exchange Rate (ACH) on Indoor Concentrations of 4-PC from New Carpet

rates on 4-PC air levels. Their results showed that increasing ventilation from 0.1 to 2.0 air changes per hour (ACH) results in a corresponding decrease in peak 4-PC concentrations from 80 ppb down to less than five ppb (see Figure 1).

The five ppb peak occurs faster — within the first day — at the higher ventilation rate. At the lower ventilation rate the calculated 80 ppb peak occurs about two days after installation. At the end of the period (28 days), the 4-PC concentrations were about 10 ppb at the lowest ventilation rate and near 0 ppb at the highest rate.

Effect of "Airing Out" Carpet

Tests at the University of Arizona by Mark Van Ert and at the EPA's laboratory in Research Triangle Park, North Carolina, showed that levels of 4-PC decline rapidly after the initial burst following carpet installation. At the Air Industrial Hygiene Conference in San Francisco in May 1988, Van Ert reported on 4-PC air levels in a residence. He said 4-PC levels were around 30 ppb when the carpet was new, and that they had declined to less than 4 ppb after four weeks. The researchers found evidence that increasing ventilation rates lowered the short-term 4-PC air levels.

Van Ert also confirmed that 4-PC was the chemical associated with "new carpet odor." He said that the odor threshold for 4-PC was 3 ppb, perhaps less than 1 ppb for sensitive individuals.

EPA investigators calculated that airing out the carpet for a month before installation in a building with 1.0 ACH would result in peak concentrations less than one ppb. Not airing out the carpet would result in a peak concentration of nine ppb, falling to about five ppb after one week and about one ppb after one month. Airing out the carpet just for one week accomplished almost half of the reduction achieved by the full month of airing-out time. (See Figure 2.)

4-PC Levels in Various Carpets

Not all carpets emit 4-PC or the same quantities of 4-PC. In an ef-

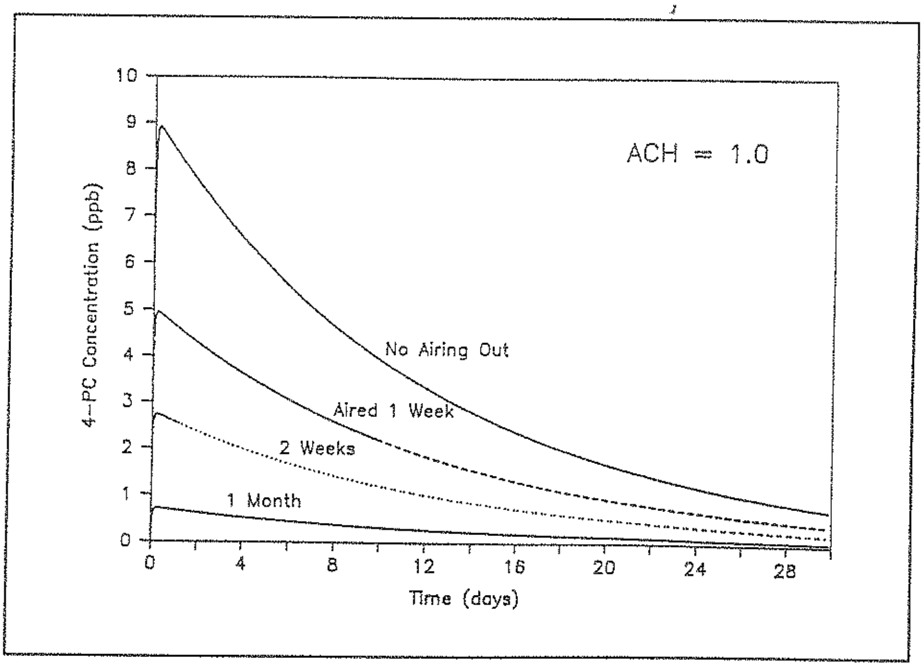

Figure 2 — Effect of Carpeting Airing Out Prior to Installation on the Indoor Concentrations of 4-PC

fort to find a less problematic carpet for EPA's troubled headquarters at Waterside Mall, researchers tested two candidate carpets and compared the results to the "problem" carpet installed and removed earlier. The analysis of extracts from all three carpets showed 4-PC levels of 61 and 24 µg/g (ppm) for the two "alternate" carpets and 116 µg/g for the "problem" carpet. The researchers concluded that the odor from the alternate carpets will have a shorter lifetime than from the "problem" carpet.

Surge of Carpet Emission Testing

We are aware of carpet product emission testing now occurring in the United States, Denmark, and Germany. In the United States, some carpet manufacturers and their trade association are engaged in carpet emission testing. The manufacturers are responding to public concern, and the results are likely to be considerable improvements in carpet products over the next two or three years. It is also likely that a standard test method for measuring carpet emissions will be developed, either by the manufacturers or, at least, with their cooperation and participation through ASTM.

The American Textile Manufacturing Institute (ATMI) is conducting carpet sample testing in chambers. From these tests it may develop standard chamber-testing techniques for carpets. The industry association is trying to take a pro-active rather than a reactive position in response to the surge of interest and concern.

In Denmark, Ole Fanger's research group at the Technical University of Copenhagen is using his subjective odor evaluation methods to study carpet emissions in room-size test chambers. They are evaluating various carpet products over an extended period of time and are comparing carpet products to each other and to the standards for odor emissions established by Fanger and his collaborators at the university. The results will allow for the evaluation of carpets in relation to other sources of indoor air contaminants.

Carpet Emissions Studied in West Germany

Bernd Seifert has reported on work by the Institute for Water, Soil, and Air Hygiene in West Berlin. In the paper, "Volatile Organic Compounds from Carpeting," presented at the 8th World Clean Air Congress in September, he concluded that carpet emissions can be the source of complaints and SBS symptoms. The researchers found several chemicals emitted from carpet or carpet adhesives that might give rise to odor and SBS-symptom complaints.

The Carpet

The researchers described the carpet they studied as "polyamide [nylon] carpeting with a laminated fabric backing and...adhesives and ancillary products." They performed both laboratory and field experiments using various sampling and analytical techniques. We describe their work in substantial detail because the methodology may be useful to researchers and investigators of indoor air complaints attributed to carpet.

The chamber test results showed that 4-PC was the major component emitted by the carpet. Table 1 shows the ten most prevalent compounds emitted by the carpet.

Temperature Effects

Researchers sampled the headspace in a 100-ml flask con-

Table 1 — Relative concentrations of 10 of the most important compounds in the gas phase above new carpeting at 0.6 air changes per hour.

Number	Compound	Percentage of total emission*
1	4-Phenylcyclohexene	30
2	Styrene	7
3	n-Dodecane	6
4	n-Undecane	5
5	1,2,4-Trimethylbenzene	5
6	unidentified	4
7	4-Methylethylbenzene	3
8	2-Ethylhexanol	3
9	unidentified	2
10	n-Propylbenzene	2

*100% = Total area counts of the gas chromatograms

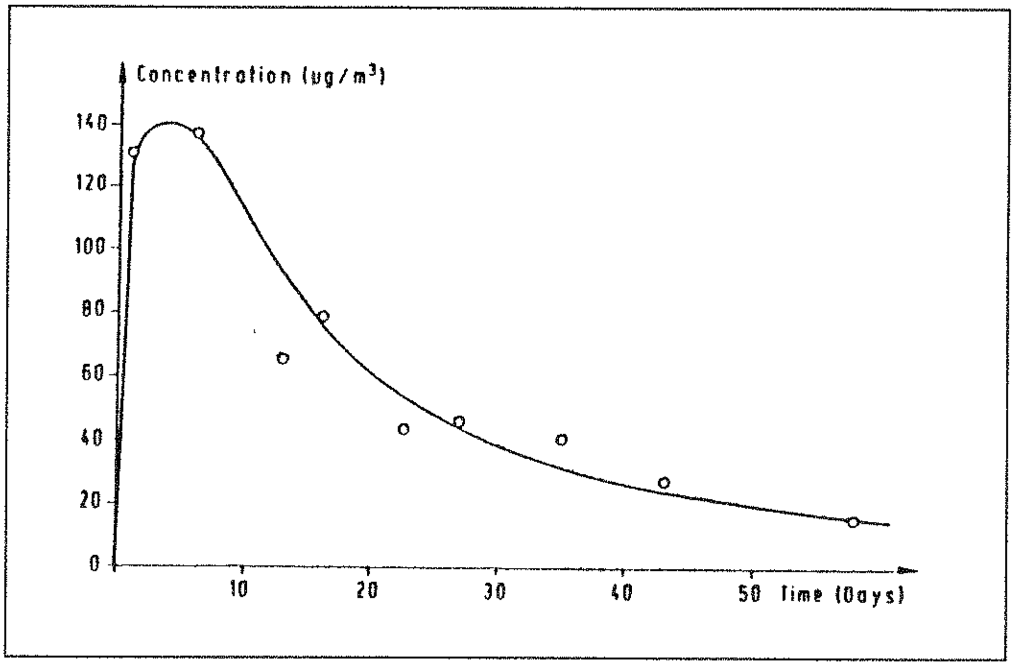

Figure 3 — Decay of 4-phenylcyclohexene in a 1-m^3 Test Chamber Loaded with New Carpeting (75 cm x 85 cm). Air Exchange Rate: $0.6h^{-1}$.

The ratio of sample area to chamber volume is called the "loading factor" in emissions testing. The loading factor was measured as units of m^2/m^3; the area of carpet is in m^2 and the volume of the chamber is in m^3. When the loading factor and the air exchange rate are numerically equal, the concentration in the air is also the emission rate.

taining six 10-cm^2 pieces of carpet. They calculated emission rates of 30 and 150 μg/m^3-hr at temperatures of 24 and 50° C from measurements with charcoal tubes. These emission rates are not convertible to concentrations since the ratio of cut edges to total surface area was much larger than in actual practice.

[Note that the increase in emissions at the two temperatures is greater than what we can attribute to vapor pressure differences alone; the difference is only an increase from 297 to 323° Kelvin, or about 9%. Yet the emission rate increased by 500%.

There are two important points here. First, this dramatic increase is not explained by accepted theory of the effect of temperature on vapor pressure. Second, this large an increase suggests that carpet emissions might be extremely susceptible to the influence of temperature. Thus, a bake-out procedure that elevates carpet temperature even 10 or 12° C might cause substantial emissions. It would be very useful in driving VOC from the carpet. However, bear in mind that the headspace test was done with purified nitrogen. In the real world, a bake-out would be difficult to orchestrate that would both elevate the temperature of the carpet substantially and provide clean air to the carpet surface. Ed.]

4-PC Decay Rate

To determine the decay rate of 4-PC emissions, the researchers measured the air levels in a 1-m^3 chamber with an air exchange rate of 0.6 ACH. The results shown in Figure 3 are for a test lasting two months. As other researchers have also found, the concentrations immediately go very high, begin to decay rapidly, then steadily decrease as the emissions approach a steady state.

Adhesives and Related Products

The researchers obtained limited information from the manufacturer about adhesives used to install the carpet. Table 2 lists that information and the results of headspace tests taken directly from the container in which the product was obtained.

This type of headspace testing does not provide emission rate data. These results represent the content of the gas phase above the product in the container, not the composition of the product nor the emission rate. The results do indicate the likelihood of finding the respective VOC in room air where the carpet is installed. The authors caution that the calculation is based on analysis of only one sample: it may be considered accurate only to within a factor of two.

Field Experiments

Carpet emissions investigations in the field consisted of measurements in 12 offices. Group I, consisting of six offices, was monitored starting the third day after installation of new carpeting. Group II, consisting of three offices, was monitored starting about

Table 2 — Composition of adhesives and related products obtained from the manufacturer and determined by static headspace analysis.

	Manufacturer's specification			Analysis	
Product	Compounds	Content (%)	Other ingredients	VOC in head space	Content* (%)
Adhesive I (water-based)	Xylene	4	Acrylate copolymer	m-Xylene	51
	Methanol	2	Colophonium resin	Ethylbenzene	23
	Phthalates	1	Filler	o-Xylene	14
	Polyglycol	1	Thickener	Toluene	7
				Methyl acetate	2
Adhesive II (water-(based)	Toluene	4.5	As Adhesive I, plus	Toluene	98
			Emulsifier (0.3%)	Ethyl acetate	0.5
			Antifoaming agent (0.2%)		
Wash primer	Styrene/acrylate dispersion	no info	Antifoaming agent	Toluene	82
			Detergent	2-Chloro-1,3,-butadiene	2
			(0.1% each)	Styrene	1
				1,2,4-Trimethylbenzene	1
				1-Methyl-4-(1-methyl-ethyl benzene	1
Filler (2-component acrylic resin	Methylmethacrylate	no info		Methylmethacrylate	99.9
	Benzoylperoxide	no info		4-Methyl 2-pentanone	0.1

* 100 % = Total area counts of the gas chromatograms

one month after carpet installation. Group III, also consisting of three offices, served as a control; no carpet was installed.

In each room the investigators located a passive sampler near the center of the space about four feet above the floor. They asked the occupants to maintain the usual ventilation in their spaces. Active sampling with charcoal tubes was carried out for one-hour periods. Two consecutive samples were collected in a Group I room and one sample each in one Group II and one Group III room.

Table 3 shows the results of the field measurements.

The researchers reported the five most prevalent VOC emissions they measured.

The results in Table 3 show that besides toluene and xylene — the solvents in the adhesives and other products — the main substances

Table 3 — Average concentrations (and ranges) of 5 major VOC in the air of Group I, II, and III rooms

Compound	Concentrations (µg/m^3)					
	3 days after laying of carpeting (Group I)		4 weeks after laying of carpeting (Group II)		Control (Group III)	
4-PC	38	(29-45)	15	(12-17)	<1	(<1)
Styrene	23	(16-30)	8	(5-13)	3	(2-4)
2-Ethylhexanol	40	(24-72)	17	(11-26)	<1	(<1 to 1)
Toluene	2000	(1200-2400)	300	(190-400)	21	(10-27)
m/p-Xylene	21	(18-29)	17	(10-27)	6	(6-7)

the carpet emitted were 4-PC, styrene, and 2-ethylhexanol. The toluene concentrations decayed rapidly, but even after four weeks it was still the most abundant single VOC measured by the tubes.

The Study Authors' Conclusions

The authors' conclusions agree with Van Ert's earlier finding that 4-PC is responsible for the carpet odor. They state that the 4-PC concentration can reach 50 $\mu g/m^3$, although they measured no 4-PC levels above 45 $\mu g/m^3$ and the average was 38 $\mu g/m^3$ for the six rooms in Group I.

The investigators also found styrene and 2-ethylhexanol, which they said is formed during the manufacturing process of the carpet backing. These are known irritants. They compared the level measured in the offices to results from a randomized sample of 500 German homes. The levels in the offices were about 10 times higher than the 90-percentile levels in the German houses. Even after four weeks the styrene levels remained much higher than in the Group III control offices.

The 2-mg/m^3 toluene level three days after carpet installation was very high. Toluene was assumed to emanate from the adhesive, and three days after installation it should have declined a great deal from its initial levels. The authors suggest that the high toluene levels, either alone or in combination with the 4-PC or other VOC, may be the cause of occupant complaints and may be partly responsible for the effects of sick building syndrome. In a previous study, the authors had measured toluene levels as high as 30 mg/m^3 from a carpet adhesive containing twice as much toluene as in the present study.

IAQU Comments

Few studies measure emissions from product samples along with emissions in buildings where the products have been used. One study that did was the Public Building Study by EPA described in *IAQU*, December 1988. In that study, carpet adhesives' measured emission rate of all "target" VOC was 234 $\mu g/m^2$-hr compared to only 36 $\mu g/m^2$-hr for carpet.

The large difference between the "wet" product (adhesive) and the "dry" product (carpet) holds true for various "wet" and "dry" products. Wet products are those applied in the building in a fluid or liquid state whereas dry products are essentially "cured" at the point of manufacture. In the EPA Public Buildings Study, the highest emissions rates were all from wet products.

The Curing Process

Wet products usually contain solvents, water, or both, which tend to be emitted rapidly, at least at first. In some products, such as caulks and adhesives, if the cross-sectional area of the applied material is large enough, a dry layer is formed at the surface resulting in an "encapsulation" of the "wetter" solvent deeper in the material. This explains the very high initial emissions rate followed by a rapid decay.

At first, emissions tend to be primarily by evaporation. But after a dried layer forms on the surface, the remaining solvent must migrate or diffuse through the surface layer. This migration or diffusion process is much slower than the initial evaporation and becomes even slower as the dry surface layer thickens.

Many dry products such as particleboard and carpet could by cured after production in order to reduce the IAQ problems in completed buildings. These products are generally packaged, stored, and transported in wrapping intended to protect them from damage or soiling. However, this same packaging often results in minimal escape of chemicals from the products between manufacture and installation.

Carpet and furniture manufacturers have told us that their products are subjected to elevated temperatures during manufacturing; therefore, they believe, most of the VOC should be driven off already. However, much of this heating occurs in closed or only partially ventilated chambers. To be effective, a final curing stage should involve very high air exchange rates, perhaps in the range of one air change per minute.

Evaluating Products on the Basis of Emissions

In evaluating the emissions of different materials and products used indoors, it is important to evaluate the relative contributions of various types of products to indoor air contaminant levels. Learning about the emissions process and characteristic emissions from important types of products can result in informed decisions by designers, facilities managers, and building users. There are a myriad of products to learn about, but by requiring manufacturers and suppliers to provide information about chemical content and emissions for their products, we can make intelligent choices.

The increasing attention to indoor air quality is leading to a rapid increase in product testing. Thus, the number of manufacturers that can provide information on their products' performance is growing rapidly. It is also leading many of them to clean up their own acts. In recent years, many formaldehyde-containing products have been improved to reduce emissions greatly. The work of insistent specifications writers and buyers and of responsible producers is already resulting in cleaner indoor air.

For More Information

B. Seifert, D. Ullrich, and R. Nagel, "Volatile Organic Compounds from Carpeting" in Man and his Ecosystem; Proceedings of the 8th World Clean Air Congress. Held at The Hague, 11-15 September 1989. Amsterdam: Elsevier Science Publishers, 1989. Available in the United States and Canada from Elsevier, 655 Avenue of the Americas, New York, NY 10010.

Contact Dr. Bernd Seifert at the Institute for Water, Soil, and Air Hygiene, Correensplatz 1, D-1000 Berlin 33, West Germany.

Tools and Techniques

More on Measuring Ventilation Rates

Last month in *IAQU* we explored ventilation measurement issues, including the use of CO_2 versus tracer gas and different CO_2 measurement methods. This month we continue our discussion. First, we comment on whole building average ventilation rate measurements versus single space measurements. Second, we discuss defining and measuring ventilation effectiveness and ventilation efficiency.

Whole Building Average Versus Single Space Values

Since whole building average ventilation rates may mask variations among spaces within the building, some investigators are critical of their use. We think they are useful as long as a sufficiently representative sample of single space measurements is made and the range and distribution of single space values is reported. The general tendency, however, is simply to report whole building average values. Most commonly used measurement methods encourage this tendency.

We have seen large variations in single space ventilation values within buildings. We think it is particularly important to report ventilation rates for spaces where other measurements are made: for example, measurements for contaminant levels. Since ventilation rates found within a building can easily vary by factors of five to ten, and since such variations can easily affect many contaminant concentrations by factors of two to five, it is extremely important that reported contaminant concentrations be correlated to a simultaneous ventilation rate measurement in the same space.

This is not a trivial task, nor do we have any recommendations for simple ways to do it. However, it can and should be done, at least in a meaningful investigation or compliance measurement routine. Much work is needed to develop simple, economical means to make ventilation rate measurements routine where contaminant measurements are made.

Ventilation Effectiveness and Efficiency

The concept of ventilation effectiveness is particularly important because the new ASHRAE ventilation standard requires consideration of it in the design assumptions. Unfortunately, there is confusion about what it means in the standard; there is no clear description of how ventilation effectiveness is to be measured.

Definitions

Many similar terms are used in discussions of ventilation measurements, and many authors make different uses of the same terms. Some of the terms frequently used are ventilation, ventilation rate (air change rate), ventilation effectiveness, and occupied zone.

We use these terms as consistently with prevalent use (where it exists) as we can. However, we caution you to remember that there are different and conflicting uses of these terms. Our advice is to understand the fundamental concepts and always clarify in your own mind what is being described, measured, reported, or referenced when the terms are used.

The following definitions are from ASHRAE's *Terminology of Heating, Ventilation, Air Conditioning, and Refrigeration* (1986)

Ventilation

"The process of supplying or removing air by natural or mechanical means to or from any space. Such air may or may not have been conditioned."

Ventilation Rate (air change rate)

"The number of complete air changes per unit of time."

While not inaccurate, we think the ASHRAE definition of air change rate is too simple. The result, particularly when it comes to measurements, is imprecision which can be significant: perhaps up to 15% of measured or designed values. (See the article in last month's ***IAQU*** for more on this issue.)

A more useful definition is that air change rate equals the ratio of the volume of the outdoor air entering the enclosed space per hour to the effective volume of the enclosed space. In other words, it is the number of times per hour the room air is replaced by outdoor air. It must consider the volume occupied by objects in the space and not just the gross volume of the enclosure or building.

The following definitions come from ASHRAE Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality" (1989).

Ventilation Effectiveness

"The ventilation effectiveness is defined by the fraction of the outdoor air delivered to the space that reaches the occupied space."

Professor James Woods of Virginia Tech says that there is an error in the definition of ventilation effectiveness, either typographic or otherwise. He asserts that the sentence should end saying "...that reaches the occupied zone" rather than "...occupied space." His assertion is consistent with language in the standard immediately before the definition.

"The values in Table 2 define the outdoor air needed in the occupied zone for well-mixed conditions (ventilation effectiveness approaches 100%)."

[Table 2 of the ASHRAE standard lists the quantities of outside air per person per minute required to comply with the ventilation rate procedure in the standard. Excerpts from Table 2 were in the October ***IAQU***.]

Occupied Zone

"Occupied zone: the region within an occupied space between planes 3 and 72 in. (75 and 1800 mm) above the floor and more than 2 ft (600 mm) from the walls or fixed air-conditioning equipment (see ASHRAE Standard 55-1981.)"

Simple Ventilation Assessment Methods

Tracer gas methods are the preferred way to measure ventilation effectiveness and efficiency, but they are expensive and demanding. Some simple, easy methods are available for short-term analysis of ventilation and air movement.

The Bubble Method

The bubble method aids visualization of air flows within a space. It is a qualitative method that can show the air currents within a room and help identify potential sources or inlets for contaminants coming from other spaces.

The simplest way to use the bubble method is with commercial soap bubbles available in most variety or drug stores. The bubble method has many advantages over other methods. Besides being economical, it is flexible, easy to control, and provides quick results.

The disadvantages include the fact that the bubbles are not "neutral density." That is, they do not possess exactly the same buoyancy as the air in the room. They are made up of exhaled breath and soap fluid. The breath is warmer than room air and the liquid film of the soap fluid is heavier than air. As they cool, they tend to lose altitude, and this descent may be misleading.

Helium Balloons

Balloons can be inflated with a quantity of helium that will make them neutral with respect to the density of room air. Such balloons can be used as visual tracers of air movement. The limitations are that balloons can become stuck between objects, static electric charges can affect their free . movement, and they can lose gas or be broken easily. However, they are simple to use and can be quite helpful in very high or very large spaces.

Smoke Tubes

Drager, SKC, and other industrial hygiene equipment suppliers make smoke tube kits. The tubes are similar to detector tubes (such as those we described for use in measuring of CO_2 in last month's issue.) With smoke tubes, an aspirator bulb forces air through the tube producing a visible "smoke." This is not a combustion product but, rather, an aerosol that becomes visible as moisture condenses on the molecules. Some of these "smokes" are acidic: we must consider occupants when the smoke tubes are used.

The smoke shows a visible trace of air movement without the significant buoyancy problems of the soap-bubble method. Smoke tubes can be used at edges of cracks in door and window frames. Or, doors can be opened slightly, then a puff of "smoke" can be released to determine the flow from one space to another.

When using the smoke tubes at doorways, it is important to observe flows at both the top and the bottom of the opening since the flows may be in opposite directions. The net flow between spaces will be indicated at the vertical mid-point of the opening.

These measurements are particularly useful when used in conjunction with air exchange rate measurements that require information on air movement between spaces to provide a reliable assessment. They are also useful in tracking down contamination in a space when the contaminant source is thought to be outside the space.

Tracer Gas Techniques

We discussed tracer gas measurement systems last month. We now look at their applications for measuring ventilation efficiency and ventilation effectiveness. There are three basic methods of tracer gas measurements; concentration decay, constant emission, and constant concentration. They involve varying degrees of equipment, time, and personnel. All three require significant initial investments and several hours to several days for the characterization of a whole building. A room or other enclosed space with a simple ventilation system can be evaluated in half a day or less.

A limitation of this method is that fluctuating ventilation (such as variable air volume — VAV) or rapidly changing weather conditions can complicate or even invalidate the test. Also, if a small building or space is being measured, occupant movement in and out of the study space can make accurate measurement difficult.

Concentration Decay Method

This is the simplest method and can be used for measurements in a single space. The equipment required is a gas monitor (around $2,000 and up), a container of the tracer gas, and a mixing fan. A small quantity of tracer gas is released into the space, mixed thoroughly, and measured as its concentration decays through air exchange with the outside. If the tracer gas is well mixed and the airflow through the room is constant during the test, the air exchange rate is calculated as the logarithmic slope of the decay in tracer gas concentration over time.

Constant Emission Method

This method is useful for long-term measurements in ductwork or for continuous measurements in single zones. Tracer gas is emitted at a constant rate for the duration of the experiment. Emission rate and concentration are measured with automated, computer-controlled equipment. The air exchange rate is calculated as the flow rate of tracer gas divided by the product of the room volume and the concentration of the tracer gas in the air. If either the ventilation rate or tracer gas concentration change during the measurement period, then the ventilation rate must be computed using a mass balance equation.

Constant Concentration Method

This method is useful in buildings that are occupied during the measurement. A constant concentration of tracer gas is maintained in the test area. The emission of tracer gas is controlled by feedback from measurements of the air concentration. Obviously, this is an expensive method in terms of equipment, but it has the advantage of being useful under varying occupancy and weather conditions.

The air exchange rate is calculated as the average tracer gas flow rate required to maintain a constant concentration divided by the product of the room volume and the gas concentration. This method can use significant quantities of tracer gas; sensitive and accurate equipment can minimize costs over the long run.

Ventilation Effectiveness Measurements

Ventilation effectiveness is measured by injecting tracer gas into the supply air, either by pulses, constantly, or all at one time. The measurements are the same with all three methods but the calculation methods differ.

After gas is injected, a certain time period is required for mixing. This time period is a function of the room itself and the ventilation rate, but in general it will be at least one-half hour. Then measurements are made in the room (ideally at several points) and at the supply and return air registers in the space.

Age of air is the time elapsed since the gas molecules being measured entered the room, either through the ventilation system, through leakage into the space, or from source emissions within the space.

Mean Age of Air

Measurements made at the return air opening measure "mean age of air" in the space. If the room air is well-mixed, and if the air leaves the room at easily definable points, then mean age of air is a useful and reliable indicator of ventilation system performance. However, it does not quantify precisely the ventilation effectiveness. If the room air is not well mixed, if the room is leaky, if air leaves it through many exhaust system locations, or if the ventilation rate is variable, mean age of air is not useful.

Local Age of Air

In the latter case, it is important to measure at as many points in the room as possible and calculate the "local age of air." This will give a better indication of how effectively the ventilation system removes contaminants. This method also works better in naturally ventilated buildings.

The advantage of the local age of air method is that the results apply to individual locations within the building. This allows for the identification of stagnant zones — or the verification of their existence when they have been suggested by the simpler methods described previously (such as the smoke tubes and bubbles).

Air Flow Factor

The lowest age of air occurs when air flow through a room is piston-like: it moves uniformly from one side to another. This could be from one wall toward the opposite wall or from the floor or ceiling to the opposite surface. In piston flow, the oldest air is found at the exhaust.

If the air in a room is "perfectly mixed," the mean age of air will be double that in piston flow. The age of air in the whole room is equal to the age of air at all points in the room. If there are stagnant areas, the mean age of air in the room will be greater than in the perfectly mixed case. In stagnant zones, the local age of air is older than the mean age in the room.

The efficiency of the ventilation system room air exchange is calculated by dividing the local mean age of air in the exhaust by the mean age of air in the room.

Commentary

ASHRAE established a committee, SPC 129, three or four years ago to develop a standard measurement method for ventilation effectiveness. To date, the committee has been unable to resolve conflicting views among its members and has not produced a draft standard.

Recently, a subcommittee of SPC 129 met and considerably narrowed the range of measurement methods it will consider for inclusion in the standard. However, it is likely that more than one measurement method will be incorporated. And, it is not clear that each method will provide the same results. Some empirical work in the field would quickly clarify this situation, but we have not heard any proposals for such work.

Meanwhile, since most engineers, architects, and others involved in building design and construction use the ventilation rates prescribed in the ASHRAE standard as "design assumptions," measuring ventilation effectiveness is essential to determining compliance. We foresee problems in the field as well as controversies in litigation if some consensus is not reached quickly regarding the measurement of ventilation effectiveness.

Finally, we think the most valuable indicator of a ventilation system's performance regarding indoor air quality is the pollutant removal efficiency. This is indicated by the "age of air," either mean or local. Measurement of ventilation effectiveness is only an evaluation of the system performance from the air inlet (diffuser) into the space to the occupied zone. This does not address questions of duct leakage, mixing within the ductwork, and short circuiting in plenums or concealed spaces where fan coil units are used.

Ventilation effectiveness is important from an economy and efficiency perspective, but it will not necessarily provide a very reliable indicator of the HVAC system's ability to control indoor air quality:

- It is insensitive to "dead zones," which have been shown to exist within spaces.
- It is not clearly defined in the horizontal dimension.
- Its application to date has generally involved averaging measured values, which can produce results dependent upon an assumption that the air in a space is well-mixed.

Ventilation effectiveness is a useful and necessary tool for evaluating designs. It makes sure that the outside air delivered to the space reaches the occupied zone. It does not go the next step of evaluating the distribution of that air horizontally within the zone. We hope the next version of the ASHRAE ventilation standard will supplement the centrality of ventilation effectiveness with more direct indicators of HVAC performance regarding control of IAQ.

From the Field

EPA Releases Phase I of Building Study

Employees at three office buildings of the Environmental Protection Agency headquarters in Washington have complained of poor air quality and associated health and comfort problems for several years. Earlier this year, EPA officials began a systematic study of the three buildings: Waterside Mall and Fairchild Building in the District of Columbia, and Crystal Mall in Arlington, Virginia.

EPA has just released the first of three planned volumes reporting the study. Their first volume reports results from an employee questionnaire survey. The second volume will report results of environmental monitoring. The third volume will report results of the varied analyses of the employee survey and the environmental monitoring.

In addition to the results of the employee survey, the first volume also describes the methods used for the environmental measurements. Indoor air quality investigators will find the information valuable in assessing the methods they employ for their own field measurements.

The study is significant because it is probably the largest systematic study of problem buildings undertaken in the United States. At least, it is the largest such study done for a public agency where results will be made public. Much controversy has surrounded the EPA management's handling of the problems at Waterside Mall. In the October 1989 ***IAQU*** we briefly described the considerable criticism aimed at EPA and GSA officials during a Congressional hearing on indoor air legislation.

Many investigators insist on administering a questionnaire before doing environmental measurements. We do not believe this is an absolutely inviolable rule, but the use of questionnaires is usually valuable. Questionnaires are considerably more economical and easier to administer than environmental monitoring. And they can often identify or narrow the sources of problems in a complaint-ridden building. The EPA study at Waterside Mall appears to have done that.

The results of the employee survey are important by themselves for several reasons. First, some clear-cut patterns of distribution of complaints emerged from the results. These sorts of patterns are what every building investigator hopes for; this is especially true in a building as large, complicated, and diverse as Waterside Mall. It allows for the location of environmental measurements in areas likely to show problems and in other, less-troubled areas for comparison.

Second, the responses themselves suggest some areas requiring engineering analysis and remediation. Of course, anyone who has spent any time at the building does not need an expensive and elaborate questionnaire survey to know that many parts of the building complex are uncomfortable during many times of the year. We regularly visit an office there where the temperature reaches the upper 80s. The survey results indicate a need for an intensive investigation of the performance of the ventilation system.

Study Design

A research team developed and distributed a health and comfort "self-administered" questionnaire to an estimated 4,900 employees in the three buildings. The questionnaire contained questions on the following topics:

- Location and description of workstation.
- Amount of time spent at workstation and in the building.
- Health symptoms experienced in the building during the previous week and year.
- Relevant health information: smoking habits, allergies, asthma, etc.
- Eye, nose, throat, or other respiratory irritation from ETS or other chemicals during the prior year.
- Gynecological problems during the past year.
- Comfort issues: temperature, humidity, air movement, noise, dust, light, odors.
- Job characteristics including satisfaction and stress.
- Education, job pay plan and grade, and job classification.

Researchers used the findings from the employee survey to rank all rooms according to a health symptom index and comfort index. Then they selected about 100 locations in all three buildings for environmental monitoring and physical measurements, which were done three weeks after the survey. Monitoring at the locations included the following:

- Temperature
- Relative humidity
- Carbon dioxide
- Carbon monoxide

Some locations were also monitored for contaminants:

- Nicotine
- Biological contaminants
- Particles
- Formaldehyde and other aldehydes
- Other volatile organic compounds
- Pesticides

Ventilation measurements were also made at the locations where contaminants were monitored.

During the monitoring, researchers gave a supplemental questionnaire to employees located in the areas

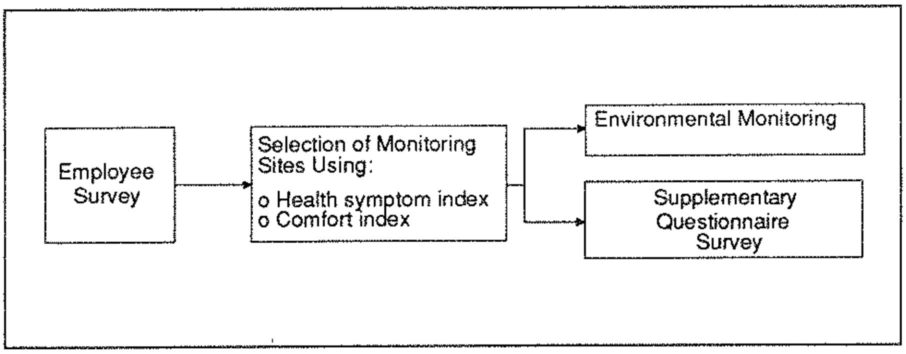

Figure 4 — The Conceptual Design of the EPA Building Study

being monitored. This allowed comparison of the environmental results and the employees' responses on the same day. Figure 4 shows the study's conceptual design.

Results

The overall response rate for the questionnaire was 81%: 3,995 of about 4,900 EPA employees. 1,400 of the respondents submitted additional comments.

The results are described below in "Health Symptoms" and "Comfort Symptoms." The report points out that these responses are "self-reported" and have not been verified by a physician's diagnosis. The Volume I report only deals with survey responses and does not try to associate them with environmental conditions in the building. That will be done in Volume III.

The Waterside Mall, the main EPA headquarters building, is a very large, complex structure housing about 4,000 employees in its twin towers and linking "mall" area. Any visitor to the building knows it more as a maze than a mall. Investigators have discovered more than one hundred separate ventilation systems, and there may be more.

In order to simplify this article from a 187-page report, we will discuss the results only from Waterside Mall unless noted otherwise. Readers wishing more detail can contact EPA and request a copy of the report (information given at the end of the article).

Health Symptoms

Building-related health symptom reports were based on whether the symptom was experienced "often or always" in the last year and whether the symptoms lessened after leaving the building. The most frequently reported symptoms were as follows:

- Contact lens wearers having difficulty with contact lenses — 28%
- Dry, itching, or tearing eyes — 17%
- Headache — 16%
- Stuffy nose/sinus congestion — 16%
- Sore/strained eyes — 16%
- Unusual fatigue 15%; sleepiness or drowsiness — 15%
- Burning eyes — 10%
- Dry throat — 10%
- Tension or nervousness — 10%

The percentages of respondents reporting other symptoms ranged from 1% to 8%.

The seven top symptoms were the same in all three buildings. The researchers grouped the symptoms into three categories as follows:

1. IAQ symptoms typically associated with discomfort such as headache; runny nose; stuffy nose/sinus congestion; dry, itching, or tearing eyes; burning eyes; dry throat; fatigue; and sleepiness.
2. Respiratory or flu-like symptoms that may manifest as illnesses that require prolonged recovery after leaving the building.
3. Ergonomic symptoms including back pain, stiffness, and pain or numbness in the shoulder, neck, hands, or wrists.

The predominant symptoms reported in all three buildings fall into the first category and are associated with poor indoor air quality. Headache, fatigue, and symptoms associated with mucous membrane irritation are frequently reported in investigations of IAQ problems.

When the analysis was changed from "often or always" to include "sometimes, often, or always," the number of respondents reporting symptoms went way up. Reported headaches and sleepiness or drowsiness both went to 41%; sore/strained eyes to 37%; dry, itching, or tearing eyes to 35%; and contact lens problems among contact lens wearers to 47%.

Productivity

Approximately one-third of the respondents stated that their symptoms reduced their ability to work at least some of the time. A quarter said their symptoms caused them to stay home or leave work early sometimes or often in the past year.

Attributed Causes

About 62% of Waterside Mall respondents associated at least one of their symptoms with working in the building, compared to 56% at Crystal Mall and 49% at the Fairchild building. Among employees who often or always experienced symptoms, between 60 and 70 percent said they got better after leaving the building.

The leading causes of eye, nose, throat, and respiratory irritation reported at Waterside Mall were identified by respondents as fumes from new carpeting, then paint fumes, followed by tobacco smoke. About one third of respondents said they were "especially sensitive" to the irritants they mentioned.

Pattern of Complaints

The researchers reported clear patterns of complaints in certain portions of the building. The second and third floor mall and the southeast mall had higher symptom rates. These sectors contained employees who were much more likely to associate their symptoms with the building than employees elsewhere. They also were more likely to say that their symptoms affected their ability to work.

Comfort Symptoms

Waterside Mall occupants reported more comfort complaints than occupants in the other two buildings, although all buildings had significant numbers of complaints. An indicator of dissatisfaction with the environment is the fact that 48% of Waterside Mall occupants reported bringing in a portable fan to their office during the previous year. Also, 22% of Waterside Mall respondents reported bringing electric heaters to work.

Occupants' desires to adjust air movement, temperature, and humidity were in keeping with the health symptoms results. Consistently, more occupants in the second and third floor mall areas wanted to adjust the environment than in the east and west towers. These two mall area floors also showed the highest health symptom rates.

For More Information

"Indoor Air Quality and Work Environment Study; EPA Headquarters' Buildings Volume 1, Employee Survey." EPA Report 19K-1003, November 1989

U.S. EPA Public Information Center, 401 M St. SW, Washington, DC 20460; (202)382-2080.

On the Horizon

More Liability for Manufacturers?

A recent decision on liability for asbestos indicates that manufacturers may have to shoulder more responsibility for their hazardous building products. A New York state judge ruled August 4 on a suit by a 50-story midtown-Manhattan building owner against former asbestos manufacturer W. R. Grace & Co. The ruling determined that the plaintiff was not a "sophisticated buyer" regarding potential hazards of asbestos. Furthermore, the building owner had no direct dealings with Grace and therefore had "no opportunity to negotiate and bargain about building requirements and the risk of loss."

Building materials purchasers today are far more sophisticated than in the past; however, they still simply do not have access to the knowledge available to manufacturers. An architect or building owner cannot afford to test or evaluate the health effects of every product or every chemical coming from every product. It is much easier for manufacturers of the products to identify potential hazards in the materials used to make their products. They can efficiently test the finished products for emissions. In today's litigious environment, more manufacturers are recognizing this and initiating appropriate actions.

Owners and specifications writers should require that manufacturers test their products and provide information about the test results. This will ensure that manufacturers are aware of their products' qualities. The specifications can also require a statement of no known carcinogens, irritants, or other health hazards. Standard, recognized lists can be referenced in the specifications: EPA, IARC, etc. The Danish government has just published lists of irritants and of central nervous system toxins as well as a list of carcinogens.

News Briefs

Indoor Air '90 Filling Up

The triennial, international conference "Indoor Air '90" has received about 50% more abstracts than "Indoor Air '87," which was held in West Berlin. This indicates that the attendance will reflect the enormous interest in the subject now blossoming on the west side of the Atlantic. If you haven't registered yet, we suggest you do so now. See listing in the calendar for details.

Massachusetts State Buildings

A bill has been introduced in the Massachusetts legislature requiring the state to develop a plan to achieve good indoor air quality in all state buildings. It authorizes the Department of Labor and Industries to "apply the ventilation codes specified in the state building codes or more stringent codes and standards, that will ensure adequate indoor air quality in buildings occupied by state employees during normal working hours." It also gives preference in leasing buildings to those which comply with the state guidelines for indoor air quality.

Furthermore, the bill authorizes a study of indoor air quality in state office buildings. The study will provide a plan for remedying cases of poor indoor air.

We do not know whether this bill, or one like it, will become law in Massachusetts. The bill is important because it reflects the growing awareness of indoor air quality and concern about indoor air problems at the state government level. Several states have been active on this issue for several years: California, Minnesota, New Jersey, Maine, and Vermont are among them. However, there appears to be a new wave of interest, which is reflected in anti-smoking ordinances in North Carolina, the Massachusetts bill, and discussions about similar legislation in Florida.

CPSC Initiates Carpet Hotline

Because of the recent, sudden increase in attention to the problems of carpet emissions, the United States Consumer Products Safety Commission (CPSC) has established a hotline to receive complaints about carpets. The CPSC toll-free hotline number is (800) 638-2772. The address for carpet problems is Carpet Complaints, Room 529, U.S. Consumer Products Safety Commission, Washington, DC 20207.

CPSC plans to collect and evaluate complaints and other evidence to determine whether there is a need for action to protect consumers. CPSC is interested primarily in residential carpet problems. But *IAQU* urges those with nonresidential carpet problems to call them also.

IAQ Update 89

Congratulations to Kelly Leovic of the U.S. EPA in Research Triangle Park, North Carolina. Kelly's name was drawn at random from those who completed the evaluation questionnaire for IAQ Update 89 — our recent forum in Washington, DC. This entitles her to a free 12-month subscription to *IAQU*.

We also want to thank all of you who took the time to complete and return the questionnaires. They will help us to make future forums even better than the first one.

Information Exchange

Strategy for Studying Air Quality in Office Buildings

This 30-page booklet, written by Nicole Goyer and Van Hiep Nguyen for Quebec's IRSST, is one of the most helpful discussions of building investigation procedures we have seen to date. It follows the usual pattern of identification, evaluation, and control. It presents these steps separately for each major group of parameters: ventilation, comfort, contaminants, and the work environment. It is distinguished from most previous guides by the amount of useful, concrete, and detailed information it contains.

It includes numerous lists of instruments for measurements and questionnaires (annotated check lists) to guide an observational inquiry. Both mathematical and instrument evaluations are described in sufficient detail that a competent professional without much prior IAQ experience could initiate an effective investigation.

The guide provides criteria for some of the major environmental parameters. It has troubleshooting types of questionnaires to guide the investigator through ventilation system evaluation, comfort-related observation, and contaminant emission sources observation. It also contains lists of control measures for various types of problems in each of the above areas.

To obtain a copy, contact IRSST, 505 boulevard de Maisonneuve Ouest, Montreal, Quebec H3A 3C2, Canada. Phone (514) 288-2614.

Practical Maintenance for Good IAQ

Another useful and handsome publication from Quebec is a manual for building operators: "Practical Maintenance Manual for Good Indoor Air Quality." It is published in loose-leaf form by L'Association quebecoise pour la maitrise de l'energie (AQME). It covers concepts of comfort and indoor air quality; how to handle complaints; problem diagnosis and solutions; prevention; verification and maintenance of components; and energy efficiency and indoor air quality.

The manual is written from an energy conservation perspective (AQME is an organization dedicated to that end). It is clearly written and presented, although the level of detail is somewhat slight, especially considering the hefty price. However, building operators might not find any other publication written just for them. It also has numerous handy checklists and practical hints.

This publication systematically goes through the variety of IAQ complaints received by building operators, describes procedures for evaluating the complaints, and provides specific solutions. It is written for a very basic level of maintenance worker without extensive engineering background or educational training.

Table 4 — Regulations and Standards for Air Quality

Parameters	Quebec	ASHRAE
	R.15	62-81R
Carbon monoxide (CO) ppm	50 (8 hours) 400 (15 min)	9 (continuously)
Carbon Dioxide (CO_2) ppm	5,000 (8 hours) 15,000 (15 min)	1,000 (continously)
Nitrogen oxides (NO_x) ppm	5 (NO_2 – ceiling) 25 (NO_2) – 8 hours) 35 (NO – 15 min)	0.055 0.40 (NO – 24 hours) 0.80 (NO – 30 min)
Ozone (O_3) ppm	0.10 (8 hours) 0.30 (15 min)	0.05 (continuously)
Formaldehyde (HCHO) $\mu g/m^3$	3,000 (ceiling)	120 (ceiling)
Nicotine $\mu g/m^3$	500 (8 hours) 1,500 (15 min)	—
Total dust $\mu g/m^3$	10,000 (8 hours)	260 (24 hours) 75 (1 year)

The appendix contains a listing of air quality standards from Quebec and from ASHRAE. A comparison of the two standards should be of interest to our readers. It is presented in Table 4.

Available in English or French (French title: "Guide pratique d'entretien pour une bonne qualite de l'air interieur"), the manual sells for US $60 including postage and handling. It can be purchased from AQME, 1259 rue Berri, bureau 510, Montreal (Quebec) H2L 4C7, Canada. Phone (514)284-2596.

Asbestos Book from A&WMA

Managing Asbestos in Schools, Public, Commercial and Retail Buildings, published by the Air & Waste Management Association, contains the proceedings of an International Speciality Conference. It is for technically oriented individuals as well as those who plan or implement asbestos-management programs in the public or private sector.

The conference, which was held in Atlantic City, New Jersey, in January 1989, provided a comprehensive assessment of how to understand, effectively handle, and reduce hazards associated to asbestos exposure.

The information in the proceedings is presented to help readers inventory asbestos-containing materials in different workplaces and public buildings by using sampling designs and microscopy techniques, prioritize asbestos abatement using a risk-assessment approach, and prepare and apply a management plan for asbestos abatement. Papers are also included on training and certification issues, state-of-the-art technologies, and regulatory and safety requirements.

This 176-page book is softbound and contains subject and author indexes. To obtain a copy, order from the Air & Waste Management Association, P.O. Box 2861, Pittsburgh, PA 15230. $60 ($40 for Association members), order code SP-66.

Calendar

January 22-23. **Indoor Air Quality Conference**, Seattle, Washington. Interagency Indoor Air Council, EPA Region 10 Indoor Air Program. Contact: Laura Lonowski, Indoor Air Division, EPA Region 10, 1200 6th Avenue, MS AT-082, Seattle, WA 98101; (206)442-2589.

January 29-30. **How to Meet New Ventilation Standards: Indoor Air Quality and Energy Efficiency.**

Houston, Texas. Contact: The Association of Energy Engineers, 4205 Pleasantdale Road, Suite 420, Atlanta, GA 30340; (404)925-9633, Fax: (404)381-9865.

February 6-8. **Georgia Tech. Research Institute Indoor Air Quality Symposium.** Atlanta, Georgia. Contact: Ann Harbert, GTRI, O'Keefe Bldg., Rm. 146, Atlanta, GA 30332; (404)894-7430.

February 9. **Georgia Tech. Research Institute Sampling and Analysis Workshop.** Atlanta, Georgia. Contact: Ann Harbert, GTRI, O'Keefe Bldg., Rm. 146, Atlanta, GA 30332; (404)894-7430.

February 11-14. **ASHRAE Winter Meeting.** Atlanta, Georgia. Contact: Judy Marshall, ASHRAE, 1791 Tullie Circle NE, Atlanta, GA 20239; (404)636-8400.

February 19-23, **The 1990 International Symposium on Radon and Radon Reduction Technology**, Atlanta, Georgia. Contact: Robert Page, Radian Corporation, P.O. Box 13000, Research Triangle Park, NC 27709; (919)541-9100.

April 4-6. **Excellence in Housing '90** — Eighth Annual International Energy Efficient Building Conference and Exposition, Denver, Colorado. Sponsored by Energy Efficient Building Association, University of Southern Maine, Technology Center, Gorham, ME 04038; (207)780-5143, Fax (207)780-5129.

April 24-26. **ASTM Subcommittee D22.05 on Indoor Air.** San Francisco, California. Contact: George Luciw, ASTM Headquarters, 1916 Race Street, Philadelphia, PA 19103; (215)299-5571.

April 26-27. **Blueprint for A Healthy House Conference.** Cleveland, Ohio. Contact: Al Wasco, Housing Resource Center, 1820 W. 48 Street, Cleveland, OH 44102; (216)281-4663.

October 1-5. **International Conference on Environmental Ergonomics IV.** Austin, Texas. Contact: Dr. Eugene H. Wissler, Department of Chemical Engineering, The University of Texas at Austin, Austin, TX 78712-1062; (512)471-7213, Fax (512)471-7060; or, Dr. Sarah A. Nunneley, USAF School of Aerospace Medicine, USAFSAM/VNC Brooks Air Force Base, San Antonio, TX 78235; (512)536-3814.

October 16-19. **Indoor Radon and Lung Cancer: Reality or Myth?** 29th Hanford Symposium on Health and the Environment. Richland, Washington. Inquiries should be addressed to Fred T. Cross, Symposium Chairman, Battelle PNL, P.O. Box 999, Richland, WA 99352; (509)375-2976.

INTERNATIONAL

April 24-26. **Indoor Air Quality and Ventilation in Warm Climates.** Lisbon, Portugal. Conference registration: Secretariat International Indoor Air Quality & Ventilation Conference, British Occupational Hygiene Society, 1 St. Andrews Place, London NW1 4LB, UK.

June 13-15. **Roomvent '90.** Second International Conference on "Engineering Aero- and Thermodynamics of Ventilated Room," Oslo, Norway. Contact: Room Vent, c/o Norsk VVS Teknisk Forening, P.O. Box 5042, Maj N-0301 Oslo, Norway.

July 29-August 3. **5th International Conference on Indoor Air Quality and Climate.** Toronto, Ontario, Canada. Contact: Dr. Douglas S. Walkinshaw, Canada Mortgage & Housing Corp., 682 Montreal Road, Ottawa, ON K1A OP7, Canada; (613)748-2714.

September 3-6. **Energy, Moisture, Climate in Buildings.** Rotterdam, The Netherlands. Contact: Mr. G. de Vries, Bouwcentrum, Weena 760, P. O. Box 299, 3000 AG Rotterdam, the Netherlands.

READERS...

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