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VOCs: Sources, Emissions, Concentrations, and Design Calculations

This article provides general guidance regarding the sources, emissions, and concentrations of volatile organic compounds (VOCs) typically found in indoor air. Included are ranges of reported values for VOC concentrations in indoor air and emissions from important indoor sources. We also describe the principal relationships between concentrations, source strengths, and ventilation. Using these data, one can more accurately calculate ventilation requirements using available emissions data and design ventilation rates.

VOCs and TVOCs

The accuracy of data about VOCs collected, identified, and quantified in indoor air depends on the measurement methods used. These include sampling media and volume, desorption methods, and analytical methods. Different measurement methods perform differently for different classes of compounds. Results can only be compared meaningfully when measurement methods are well characterized.

Researchers usually classify organic chemicals by their boiling points as being "volatile," "very volatile," and "semi-volatile." While there is no clear demarcation between various classes of organic compounds, indoor air investigators have defined volatile organic compounds (VOC) as having boiling points between 50 °C and 260 °C (WHO, 1987). Compounds with lower boiling points are classified as very volatile organic compounds (VVOC); while compounds with higher boiling points are classified as semi-volatile organic compounds (SVOC).

The focus of most emissions testing is on VOCs and formaldehyde (HCHO). HCHO and other low molecular weight aldehydes are usually reported separately because they require different measurement methods from those used for most other VOCs.

VOC air concentrations measured in occupied non-industrial buildings are often reported as total volatile organic compounds (TVOCs). The simplest definition of TVOCs is as the sum of the air concentrations of the individual VOCs. In practice, VOCs are measured in various ways and the details of the measurement methods operationally define TVOCs (Hodgson, 1995).

The common measurement methods, even when used correctly, inaccurately estimate the true concentration of all VOCs due to method-specific limitations on the compounds that can be collected and analyzed (Wallace, 1991; Hodgson, 1995). Compounds with very-low or very-high volatility are not measured by most of the methods in common use. Sorbents tend to selectively collect certain types of compounds, often dependent upon polarity. Some sorbents retain certain compound types during the extraction process. Artifacts may also occur.

Many authors report as TVOC concentrations values that in fact are the sum of the individual VOCs (Sum-VOCs or ΣVOCs) that they have identified and quantified. Others integrate the area under the chromatogram resulting from analysis by gas chromatography. Choice of detector and calibration of the chromatographic response are important determinants of TVOC quantification. Obviously, TVOC values calculated by sum-

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ming all of the integrated peaks, identified and unidentified, or by integrating the total area under the chromatographic curve, will be larger than values calculated by summing only the identified peaks – ΣVOC.

Hodgson has described the various methods for quantifying TVOCs in a review article in the journal *Indoor Air* (1995). He described the sampling methods most commonly in use as well as the most commonly used analytical methods including gas chromatography-mass spectroscopy (GC/MS) and GC with a flame-ionization detector (FID). Some methods, particularly those methods employing infrared (IR) detectors, must be calibrated accurately for the mixture of compounds actually present or else they will significantly distort the TVOC or SumVOC values obtained.

TVOC Data Interpretation

There is a high degree of uncertainty in all of the methods that are used to measure TVOCs. Values can either be overestimated or underestimated due to limits on the compounds that are collected and analyzed and to the variations in the responses of individual compounds (Hodgson, 1995). Different classes of compounds have dramatically different responses with methods that employ photo-acoustic or infrared detection. In all cases, the analytical response must be calibrated against the response of a specific compound or mixture of compounds. The selection of the calibration compound introduces additional uncertainty. Thus, it is essential to know the sampling and analytical methods that were used to obtain any TVOC concentration in order to evaluate the potential uncertainty in the method. Despite these uncertainties, the most commonly used methods for measuring TVOCs may be consistent within a factor of about two for typical samples of indoor air in the absence of a dominant source.

Most of the common methods for measuring TVOCs and VOCs may not detect organic compounds with very-low or very-high volatility. Low volatility, or semi-volatile compounds, may have important health implications since they include pesticides and other chemicals known to be toxic to humans. Formaldehyde, a ubiquitous and highly irritating compound, is an example of a very volatile chemical that must be analyzed using specialized methods.

Concentrations

Data from VOC field measurements are useful in providing information on normal or typical concentrations. Concentrations of VOCs are determined by many factors including the VOC concentration in the outdoor air, the ventilation rate, the removal of contaminants by adsorption, the re-emission (or desorption) from sinks, and changes due to chemical reactions among the VOCs and with other types of chemicals.

Residential VOC air concentrations generally tend to be higher than those in non-residential buildings (Brown *et al.*, 1992). Wallace *et al.* (1987) reported a mean TVOC concentration for a sample of 200 homes representative of a population of about 600,000 residences in the US at 0.7 mg/m^3. Brown *et al.* (1992) reported 1.13 mg/m^3 as a weighted averaged geometric mean (WAGM) for 1081 residences measured by several investigators in several countries.

Several major non-residential surveys, each using a single, well-documented method for measuring VOCs in multiple buildings, provide a valuable database useful in determining typical or normal VOC concentrations. Several of these studies are described in more detail below. The most common measurement methods used in these surveys include the active collection of air samples on sorbents such as Tenax™ or charcoal or on multi-sorbent tubes. An analysis of recent literature by Hodgson found the most commonly used sorbent is Tenax. Some studies, especially the Building Assessment and Survey Evaluation (BASE) Study conducted for the US EPA, use evacuated summa-polished stainless-steel canisters to collect air samples. However, the results from this study have not yet become available. Comparison of preliminary results to those indicate reasonable agreement with measurements by other methods (Girman, 1995).

In the major multi-building non-residential indoor air surveys, most reported TVOC or SVOC values are in a range from less than 0.15 milligrams per cubic meter (mg/m^3) to 1.0 mg/m^3 (Sheldon *et al.*, 1988; Wallace *et al.*, 1991; Shields *et al.*, 1996 in press; Daisey *et al.*, 1994; Cretton 1995; Brown *et al.*, 1992; 1994). A few buildings have been reported to have concentrations above 1 mg/m^3 and even fewer above 2 or 3 mg/m^3. Occasionally, a building is reported with 10 mg/m^3 to 20 mg/m^3, and even more rarely, with concentrations of 20 mg/m^3 to 100 mg/m^3 (Tsuchiya, 1990; Levin, 1994; 1995; Brown, 1994).

The higher concentrations are usually attributable to easily identified strong sources. The most common of these include household and janitorial cleaning, hobby and art materials, reproduction equipment, and newly installed building materials (e.g., paints, sealants, and adhesives). Other sources are liquid-process photocopiers or plotters (Hodgson *et al.*, 1991; Tsuchiya, 1990). Buildings other than those newly built or renovated with TVOC concentrations higher than 1.0 mg/m^3 to 1.5 mg/m^3 suggest the need for investigation of sources and mitigation either by source control, ventilation, or both.

Telephone Company Administrative Centers Survey

Figure 1 shows concentrations reported from long-term (~30 day) samples collected passively on charcoal by Shields *et al.* of Bell Research Corporation (Shields, 1993; Shields *et al.*, 1996 in press). The samples were collected at ten telephone company administrative offices throughout the United States. None of these offices was new at the time of the study, although minor construction activity was reported in some. ΣVOC concentrations were calculated by summing the concentrations of the approximately seventy individual compounds that were identified and quantified. By observation, we note that most buildings measured had ΣVOC air concentrations ranging from 0.12 to 0.83 mg/m^3 with a geometric mean of 0.28 mg/m^3. The highest concentrations were found in buildings where painting had recently occurred or where it was currently in progress. None of the ten buildings had ΣVOC air concentrations that exceeded 1.0 mg/m^3. Outdoor air ΣVOC concentrations ranged from 0.33 to 1.03 mg/m^3 with a geometric mean of 0.53 mg/m^3. The researchers reported limitations of the measurement method included loss of certain compounds and an inability to identify certain others. Shields *et al.* noted that many VOCs commonly present indoors cannot be detected by the method used in their study for various reasons.

An important difference between the Shields *et al.* study and the others reported here is the use of extremely long sampling times required for the passive charcoal badges. Compared to most active sampling methods that use sampling times on the order of hours, the 30 days typical of the Shields study is quite different. The concentrations found by Shields *et al.* are likely to include peaks and valleys whereas active sampling typically over a small number of hours may only capture an episodic VOC air concentration peak or valley. The long-term samples also included non-occupied and occupied hours and may not be representative of shorter-term values.

EPA "Public Buildings Study"

Figure 2 shows concentrations reported by Sheldon *et al.* (1989) from the EPA Public Buildings Study. This was, in fact, two separate studies conducted over a period of several years. The data shown in Figure 2 are plotted against building age in weeks. The TVOC values reported in the study were actually ΣVOC for selected target compounds only. The buildings included offices, nursing homes, homes for the elderly, and schools. The age of the building was reported in most cases. In two newly constructed buildings, measurements were made on separate occasions several weeks or months apart. This allowed observation of the trend of decaying emissions as building materials and furnishings aged. Note that both the reported values greater than 1.0 mg/m^3 were collected in two buildings sampled one week after completion of construction. Without these two data points, the trend is not so obvious and probably not significant. Also note that the

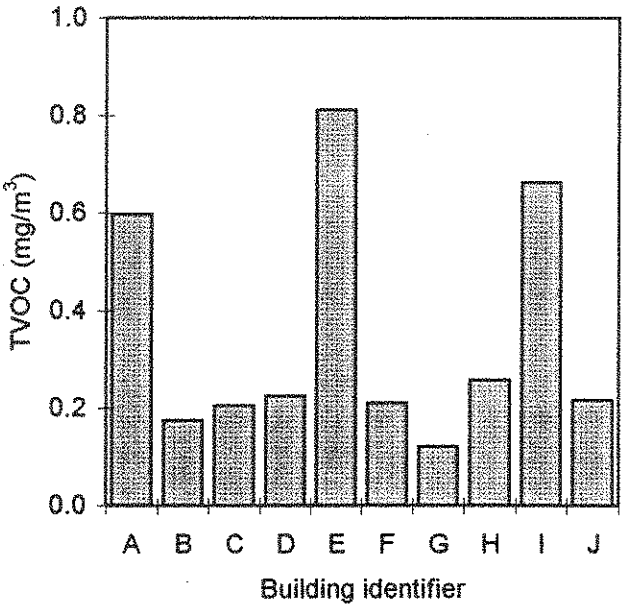

Figure 1 - Average SumVOC concentrations in telephone company administrative offices.

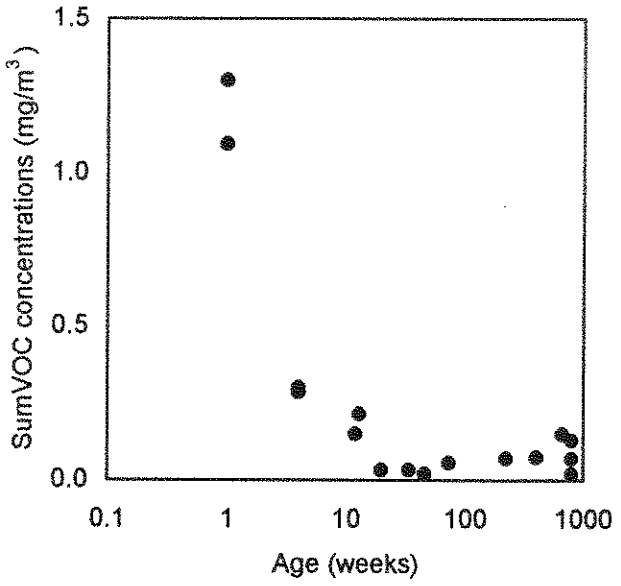

Figure 2 - TVOC concentrations from the EPA Public Buildings Study.

three data points shown in the lower right hand corner of the graph at 900 weeks were from buildings of unreported age identified as "old" by the investigators. They have been assigned an arbitrary age of 900 weeks for purposes of plotting the graph.

The TVOC concentrations generally appear low compared to data reported by others. That is due to the fact that ΣVOC are actually only the sum of the concentrations of a group of selected target VOC. Later, Wallace *et al.* (1991) attempted retrospectively to calculate a TVOC concentration for these samples. The results were derived concentration values considerably higher than the totals of the compounds reported in the original study. The derived values had a geometric mean and a median of 1.9 mg/m^3 and a geometric standard deviation (GSD) of 2.3 mg/m^3. (These numbers include the samples collected right after completion of construction and therefore are skewed to the high side.) The method is reasonable and is the basis for many GC/MS methods for TVOC that are currently in use.

There is an apparent overall trend in the data shown in Figure 2 suggesting that the older a building, the lower the VOC concentrations are likely to be. However, in one building, a hospital, the concentrations rose dramatically from the early to the later measurements. The specific compounds associated with this difference were ingredients of common cleaning and maintenance materials.

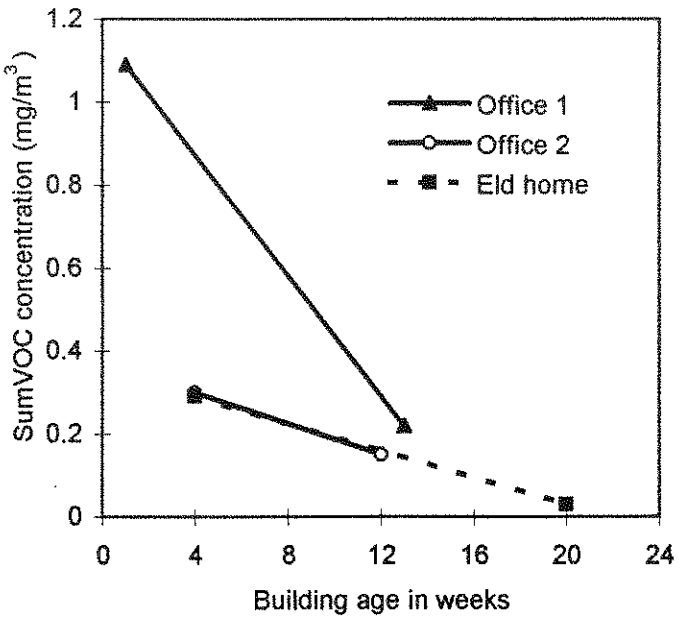

Figure 3 - VOC concentrations in three buildings as a function of time.

Figure 3 shows the decay in concentrations in three of the buildings from the EPA Public Buildings Study where concentrations were measured on multiple occasions beginning close to the time initial construction was completed. Note that there is a consistent pattern of decay in all three buildings. This suggests that the initial concentrations were elevated due to emissions from construction materials. While there is no direct proof that this is the case, data on the decay of emissions from new materials provides important supporting evidence for this conclusion.

California Healthy Buildings Study

Mendell *et al.* investigated 12 governmental office buildings in the California Healthy Buildings study (Mendell, 1991; Fisk *et al.*, 1993; Daisey *et al.*, 1994). VOCs, TVOCs, and ΣVOCs were measured using multi-sorbent tubes and GC/MS and FID in one to four locations per building as reported by Daisey *et al.* (1994). The sums of the 39 individual quantified VOCs accounted for 35 to 90% of the TVOC values excluding the buildings with liquid-process photocopiers as a source of VOC.

TVOC ranged from 0.23 to 7.0 mg/m^3 with a geometric mean (GM) and a geometric standard deviation (GSD) of 0.51 ± 0.0021 mg/m^3. The authors observed that the indoor concentrations of TVOC and VOCs were generally low except for the two buildings that had liquid-process photocopiers. In these two buildings, VOC concentrations "...were dominated by a characteristic mixture of C_{10}-C_{11} isoparaffinic hydrocarbons." Others have reported similar findings from liquid-process photocopiers (Hodgson *et al.*, 1991; Tsuchiya and Stewart, 1990; Wolkoff *et al.*, 1993). Excluding the two buildings with liquid-process photocopiers, the mean TVOC concentration was 0.41 ± 0.0016 mg/m^3. Again, excluding the two buildings, the GM and GSD for naturally ventilated buildings was 0.41 ± 0.0016 mg/m^3, mechanically ventilated buildings was 0.39 ± 0.0013 mg/m^3, and air-conditioned buildings was 0.44 ± 0.0014 mg/m^3.

ΣVOC ranged from 0.14 to 0.72 mg/m^3 with a GM and GSD of 0.28 ± 0.0015 mg/m^3. The researchers found insignificant differences in GM values of TVOC in the buildings studied (except for those with liquid-process photocopiers) regardless of building ventilation type — natural, mechanical, or air conditioned. GMs were less than 5 ppb (0.024 mg/m^3 for 1,1,1-Trichloroethane) for all compounds other than ethanol at 19 ppb (.036 mg/m^3).

Generally, oxidized hydrocarbons were the dominant class of VOCs found in each of the 12 buildings. Terpenes, alkanes, and aromatic hydrocarbons were also important classes of compounds in some of the buildings.

European Audit Project Data

Figure 4 shows VOC average indoor concentrations in 56 buildings from nine countries participating in the European Audit Project (Cretton *et al.*, 1995). The measurements were made by researchers in each of the participating countries using similar sampling and analytical methods based on sample collection on Tenax and analysis by GC/MS (Bluyssen *et al.*, 1995). The buildings were of various ages and employed a variety of ventilation strategies. None of the buildings in the study was reported to be new or newly renovated. Many of the buildings were ventilated with mechanical systems. Smoking was permitted in all or portions of some and prohibited in others. The buildings in each country were a mix of urban, suburban, rural, natural and mechanical ventilation, and old and new buildings. No consistent formula appears to have been applied for building selection.

The data indicate that with few exceptions, TVOC concentrations were less than 1 mg/m^3, and, in most cases, they were less than 0.5 mg/m^3. While there were significant variations among buildings in most of the countries, the between-country variations were also large in some instances.

TVOC concentrations plotted against ventilation rates did not show any pattern. Reported ventilation rates ranged from 0.4 air changes per hour (h^{-1}) to 10.5 h^{-1}. Country averages for air exchange rates were from a low of 0.9 h^{-1} in the UK to a high of 3.6 h^{-1} in Greece. However, Bluyssen *et al.* (1995) observed that reported ventilation rates could have varied from actual rates by a factor of two.

Ventilation and Other Factors

Ventilation and contaminant source strengths together are dominant determinants of indoor air contaminant concentrations. As ventilation increases, concentrations decrease for contaminants with predominantly indoor sources. As sources strengths increase, concentrations increase (See Figure 5.). Air cleaning and filtration can reduce concentrations. Some contaminants are removed from air by adsorption on building surfaces, although most contaminants that are so removed are also re-emitted into the air at some rate so that even after removal of the source, the contaminants may persist in the air. Concentrations of some contaminants can be changed dramatically by interaction with other chemicals such as ozone and nitrogen dioxide (Weschler *et al.*, 1992; Zhang and Lioy, 1994).

Figure 5 shows a set of ideal curves for VOC concentrations at typical source strengths and ventilation rates. The curves in Figure 5 are based on the simple relationship between only three factors: source strength, ventilation rate, and concentration. In prac-

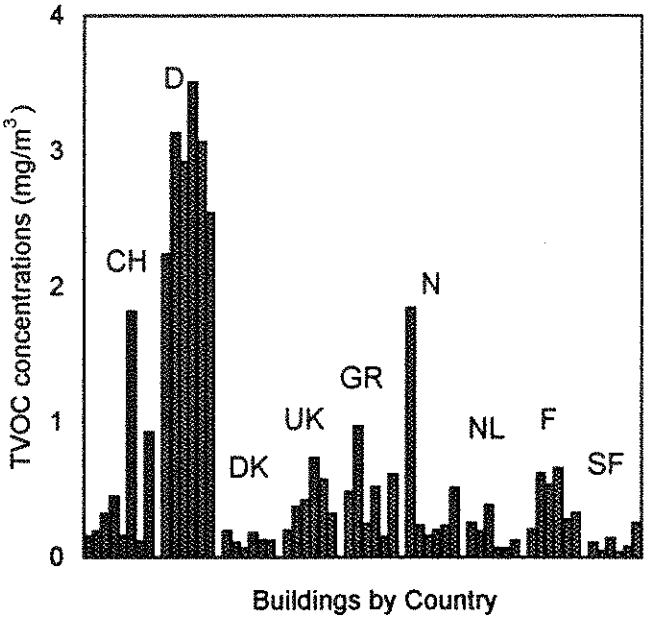

Figure 4 - Average TVOC concentrations from 56 buildings in nine countries from the European Audit Project.

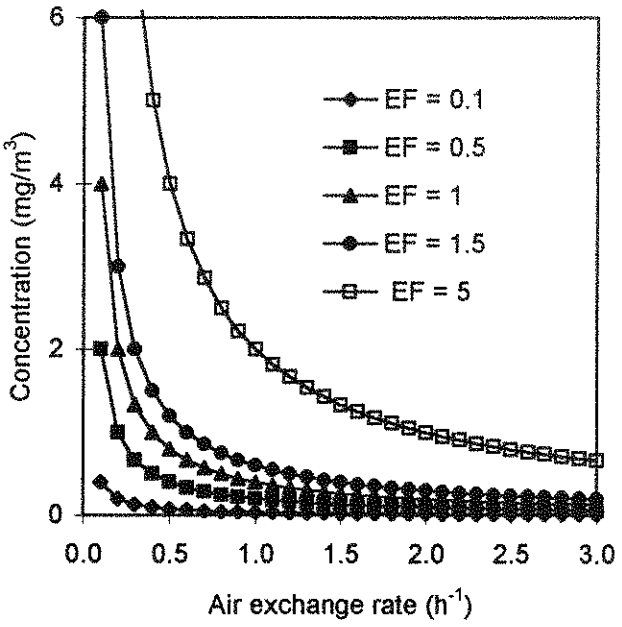

Figure 5 - VOC concentrations by source strength as a function of ventilation rate.

tice, other factors affect concentrations including the time dependence of emissions, indoor and outdoor concentrations, and removal mechanisms such as adsorption and chemical transformation (Saarela, 1994). Hodgson *et al.* (1991) have demonstrated that these simple relationships can be used to predict with reasonable accuracy concentrations from source strength data for solvents used in wet-process photocopiers. Black *et al.* (1991) have shown that emissions from a carpet assembly tested in an environmental chamber can be used to predict building concentrations from the same carpet assembly.

As can be seen in equation (1), ventilation has a direct effect on VOC concentrations. Equation (1) is often used to depict the relationship between source strength, ventilation, and the resulting concentrations at steady state in indoor air (ASTM, 1994).

$$EF = C(Q/A) \quad [1]$$

Where:

EF = emission factor, $mg/m^2 \cdot h$

C = equilibrium chamber concentration, mg/m^3

Q = flow through chamber, m^3/h

A = sample area, m^2

Equation (1) assumes steady-state conditions in order to simplify analysis. It oversimplifies the complex, interdependent relationships that determine contaminant concentrations. It also ignores sink effects and contaminant sources in outdoor air that are supplied to the interior. Concentrations can vary by a factor of 10 or more, inversely with typical ranges of ventilation for a single building, given the same source strength. Source strengths can also vary by a factor of ten or more. Figure 5 showed the relationship between concentration and ventilation for five assumed source strengths. The source strengths and ventilation rates plotted in Figure 5 span those typically encountered in buildings ranging from a reasonably low source strength (0.1 $mg/m^2 \cdot h$) to one that represents the presence of strong sources (5 $mg/m^2 \cdot h$), although stronger source strengths are occasionally observed.

It is important to note that mechanically ventilated office buildings in the United States have ventilation rates typically ranging from 0.4 h^{-1} to 1.8 h^{-1} during most operating hours over the course of a year (Persily, 1989). Within this range, there are significant differences in the concentrations resulting from the different source strengths. Examining the difference just between the lowest two source strengths, 0.1 $mg/m^2 \cdot h$ and 0.5 $mg/m^2 \cdot h$, we note that at the lower end of the ventilation rate range, there are significant differences in the concentrations plotted.

Typical minimum values of air exchange rates range from 0.4 to 1.0 h^{-1} in mechanically ventilated office buildings (Persily, 1989). Buildings with higher occupant density will have higher minimum outside air exchange rates when ventilation is based on outdoor air supply per occupant, typically 7 to 10 L/s (15 to 20 cfm). Thus, schools may have minimum outdoor air ventilation rates of 3 h^{-1} while fully occupied theaters, auditoriums, and meeting rooms may have minimum air exchange rates of 4 to 7 h^{-1}. Panadian *et al.* (1993) reviewed data on air exchange rates in US residences. Observations in 1836 residences revealed ventilation rates as low as 0.1 h^{-1} with about half of all observations ranging from 0.35 h^{-1} to 2.35 h^{-1} with an arithmetic mean of 2.0 h^{-1} and a standard deviation of 3.3 h^{-1}. The mean ventilation rates observed in summer (5.4 h^{-1}) are typically higher than those observed in spring (1.9 h^{-1}), fall (0.4 h^{-1}) or winter (0.5 h^{-1}). The mean ventilation rates in two-level homes (2.8 h^{-1}) were higher than those in single-level homes.

Emissions from most sources are probably limited by diffusion within the source. However, for those sources limited by mass transfer effects, the model used to plot the curves in Figure 5 neglects the effect of increasing concentrations at low ventilation on emission rates. As concentrations rise, emissions decrease so that the increase in concentrations is not linear. On the other hand, as we go from higher to lower concentrations by increasing ventilation, concentrations rise more rapidly than a straight line projected from concentration decreases measured at higher ventilation rates.

Air movement at the surface from which emissions are occurring will affect the emission rates. The higher the air velocity, the higher the emissions. For evaporation dominated emission processes (such as from paints and sealants), this factor may be quite important in determining the emission rates and decay curves for emissions (Iwashita and Kimura, 1994).

Temperature can also be an important determinant of emission rates since vapor pressure is a temperature dependent function and vapor pressure is the driving force for evaporation or phase change.

Sources

There are a large number of possible VOC sources in buildings. They include the building and its contents as well as the occupants and their activities. By identifying the most significant sources, control strategies can be targeted effectively and overall efficiency can be

optimized. Early in a building's life, the sources are usually building materials and furnishings. After a period of a few days or weeks, these sources decline in significance while occupant activities increase in importance as sources.

Processes and equipment or appliances can also be important sources of contaminants. After new building materials age, these usually episodic, often recurrent sources can be the dominant sources of VOCs in buildings. The study of Shields *et al.* (1996) found a significant correlation between VOC source strengths and occupant density in buildings classified as low-, moderate-, and high-occupant densities. Large contributions can come from such activities as food preparation, arts and crafts, hobbies, photocopying, building maintenance, tobacco smoking, and a myriad of other activities Consumer products such as housekeeping and cleaning products are also important sources as are those used for dry cleaning and personal hygiene. (Tucker, 1988; Levin, 1989; Girman, 1989; Colombo *et al.*, 1990).

The total mass and surface area as well as the emission rate of a product or material in a space are important determinants of the potential sources. The total mass of VOCs contained in sources establishes the theoretical limits on total lifetime emissions. Typically, a small number of sources dominate at any point in a building's life cycle. These are determined by calculated total VOC mass in products from data on their VOC content, and their area coverage and depth or application rate (Levin, 1991).

VOC Source Strengths

Air contaminant source strengths can be determined by measuring contaminant air concentrations and ventilation rates. Typical VOC source strengths for a wide range of buildings calculated from measured indoor air concentrations and building ventilation rates range from 0.2 to 1.5 mg/m^2 • h. For most buildings where these measurements have been made together, building-wide average source strengths tend to range from about 0.5 mg/m^2 • h to around 1.5 mg/m^2 • h. In very "clean" buildings, source strengths have been reported well below 0.5 mg/m^2 • h, and in many less-clean buildings, source strengths of 2 to 10 mg/m^2 • h have been found (Cretton *et al.*, 1995).

The Effect of Building Materials Aging

Emissions from most building materials change significantly over time, tending to decrease most rapidly when materials are new or newly exposed to the environment, and more slowly thereafter (Saarela, 1994). Emissions from "wet"-applied building products such as adhesives, paints, sealants, and caulks often decay much more rapidly than emissions from "dry" building products such as textiles, composite wood products, polymeric materials, and paper. Tichenor found that a significant fraction of paint applied to gypsum board was absorbed by the gypsum board and released more slowly (Tichenor, 1993). Per Clausen found that the thickness of a paint layer is an important determinant in the emissions rate. (Clausen, 1996 in press).

Different sources are important at different stages in a building's life and even at different times of a day. Some original building construction materials are usually strong sources during the early portion of their useful life; however, in most cases, they decay rather significantly during the first hours or days after installation. These materials include surface finishes, paints, sealants, and other wet products. Many materials take longer for the emissions to diminish significantly. These are mostly "solid" materials rather than surface treatments.

Figures 6 through 8 show results from emissions tests of various types of carpets. Figure 6 shows tests on four types of carpet from a study conducted for the US Consumer Product Safety Commission by Hodgson *et al.* (1992). Emissions were reported at 24 and 168 hours. While the emissions rates varied by a factor of more than six at 24 hours, all decayed significantly over the six days between the initial and final measurement. However, the large range of differences persisted at least until 168 hours. The fractional reductions over

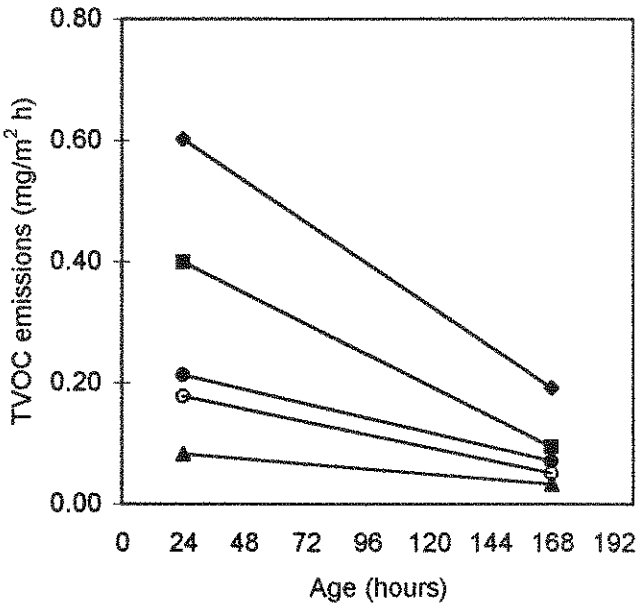

Figure 6 - VOC emissions from selected carpets by age of carpet (from Hodgson).

that time period ranged from 0.61 to 0.76, a relatively small range considering the significant differences in the types of carpet studied.

Figures 7 and 8 show results of a chamber carpet study by Tappler *et al.* of Austria (1994). All three carpets shown in Figure 7 were vinyl backed. The results show clear trends of decreasing emissions in the time frames reported. Figure 8 shows tests of five carpets with textile secondary backing. Again, the results are consistent in showing significant decays in emission during the early days of exposure to the environment.

These and many other tests of new and slightly aged building materials of various types consistently show the decreases in emissions that most likely account for a significant part of the general decline in VOC concentrations as new buildings age (Levin, 1989; Saarela, 1993). It should be noted that the time frame of the these measurements is extremely short compared to the total lifetime of the product and/or the building.

As a result of aging building materials, VOC source apportionment changes over time. Early in a building's life, emissions from building materials tend to dominate. Over time the building contribution diminishes as furnishings are installed. Both of these sources diminish in relative contribution to TVOCs as people enter with their belongings, commence their activities, and operate equipment and appliances. For older buildings, cleaning and maintenance materials often dominate VOC sources. When renovation or surface finish renewal occur, the materials used can dominate VOC sources, usually for short periods of time. The apportionment for aged buildings among the various sources differs among buildings, but the building materials themselves tend to be less significant than occupant activities and equipment.

NIST Commissioning Study

Further (convincing) evidence of the decay of emissions from new building materials and furnishings is available from a study recently reported by NIST (Dols, Persily, and Nabinger, 1995). In that study, various floors were finished at different times. The spaces were measured at three time points including immediately after completion of the interior build out, after the installation of the wall and furniture systems, and approximately one month after occupancy. The wall systems installed in the second phase were "modular floor-to-ceiling partitions used to form individual offices and conference facilities" and typical workstation partitions about 1.5 m high.

The researchers also measured ventilation rates so they could calculate source strengths, although they stated that they could not measure leakage through closed dampers and estimated it at 20% of the outdoor air flow rate through the intake ducts. Thus, they said, the calculated source strengths would have been about 20% greater than those they reported. The results, using a simplifying assumption of steady state conditions, are shown in Figure 9. The results depict a general pattern of decay from each building phase to the

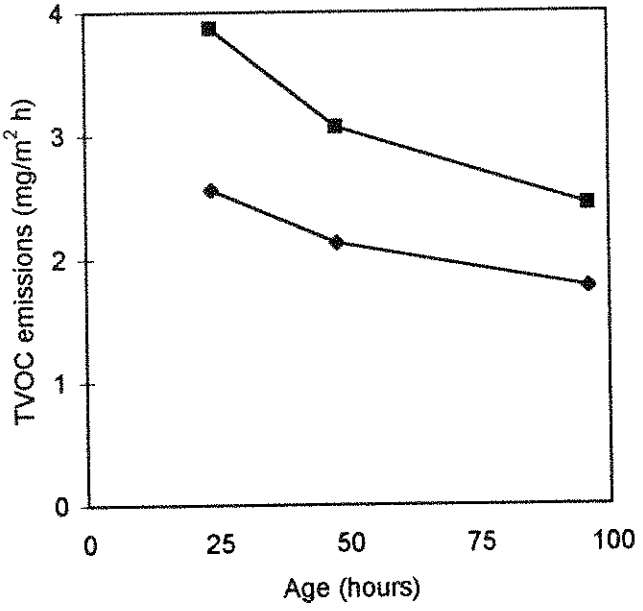

Figure 7 - VOC emissions from vinyl-backed carpet by age of carpet (from Tappler).

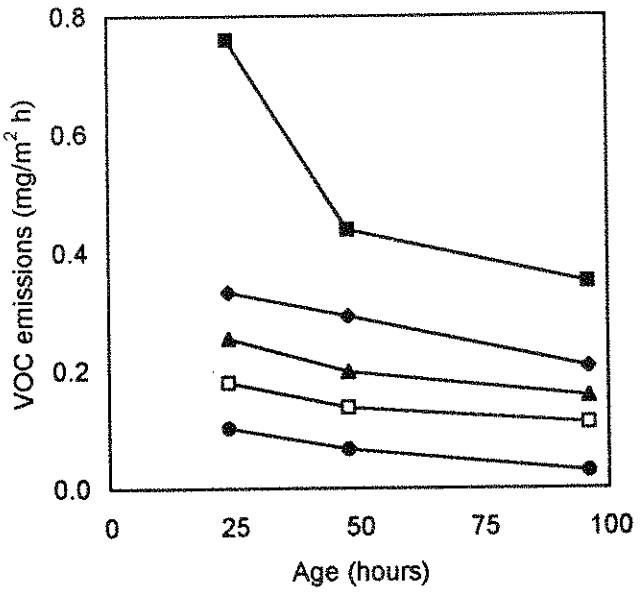

Figure 8 - VOC emissions from selected carpets with textile secondary backing (from Tappler).

next. Although the magnitudes of the initial source strengths varied considerably, and these differences were not explained, they appear to indicate that even within a single building such variations exist. Figure 9 shows VOC concentrations against time for the NIST study.

Emissions

While data on emission rates for typical sources are incomplete and imperfect, general knowledge can guide designers in selecting products and designing ventilation systems to achieve VOC concentrations that are consistent with the normal or typical range found in buildings. When target values are established for a design and emission rates are known for dominant sources, then simple calculations can provide reasonable estimates of ventilation requirements needed to attain those concentrations.

Figures 10 through 13 show emissions from various major building material types with widespread use in buildings. The data used for the graphs have been assembled from various sources published during the past decade. The figures show the quasi-steady state emission rates for the tested materials by age. There are usually significant variations in different types of products or materials in any of the classes of products shown, and these differences are reflected in the figures at various material ages. In most of these graphs, several different types of products are shown, often including considerable variation.

Note that Figures 10-13 are plotted with logarithmic scales on the horizontal time axis. There is a consistent trend in emissions decay over time in virtually all of these figures. When specific products are tested at different ages, this decay is demonstrated. For example, Tappler *et al.* (1994) tested various types of carpet at different ages and found these decayed as shown in Figures 7 and 8.

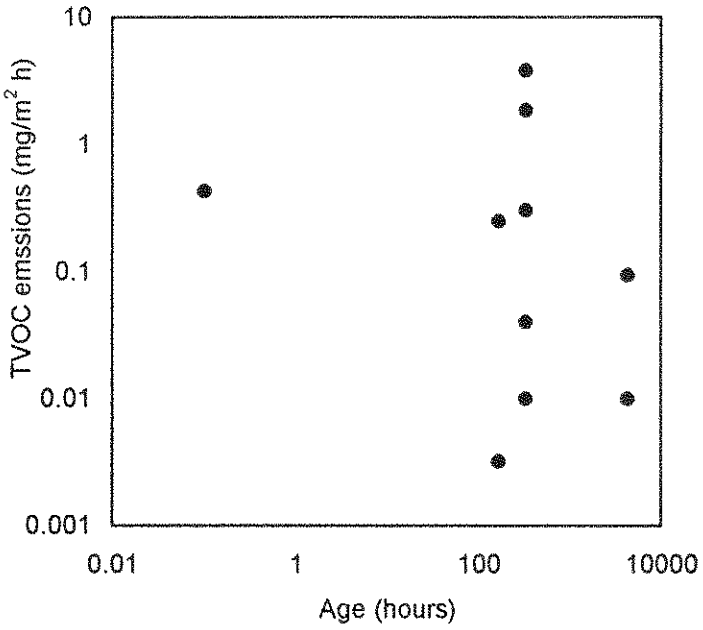

Figure 10 - VOC emissions from various paints by age since application.

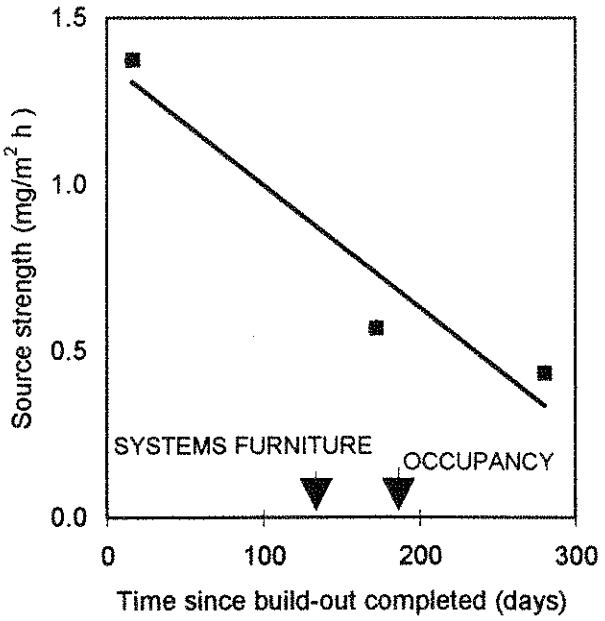

Figure 9 - VOC source strengths in NIST building commissioning study (from Dols).

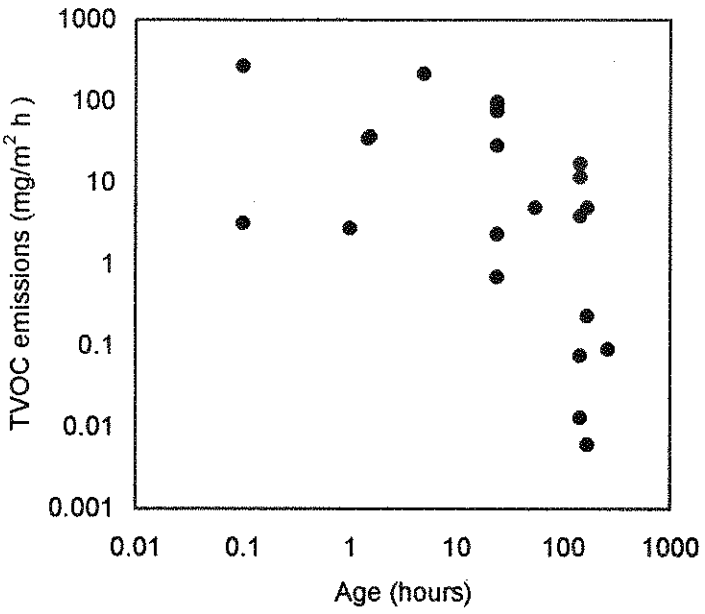

Figure 11 - VOC emissions from various adhesives by age since application.

Insufficient data are available for most product types to show detailed comparisons of interchangeable products. But the graphs do show that within a general product category, there are significant differences among products and even larger differences between types of products. These differences indicate the importance of obtaining test data when selecting building products and materials.

Emissions from Building Assemblies

Many materials and products in buildings are in assemblies such as floor coverings, walls, ceiling systems, furnishings, etc. When separate materials are assembled, the emissions from the assembly are often affected by the composition of the various assembly components. For example, as mentioned previously, paint applied to gypsum board may be absorbed to a significant degree by the drywall thus producing a different emission pattern from that of paint (or drywall) alone (Tichenor *et al.*, 1993). The result is that emission rates are lower but extend over a longer period of time than when paint is applied to a non-porous surface (such as metal or glass) as is usually done in laboratory emissions testing.

The effect of assembling materials with adhesives is an important one because many newly applied adhesives are high emitters of VOCs. This is particularly important for materials being used for floor coverings or wall coverings since these materials may have significant surface areas. The more absorption by the substrate material, the lower the initial emission is likely to be, and the longer the whole process continues. The less permeable the covering, the more likely it will slow the emission once the covering is applied. The amount of time between application of the adhesive and the covering can also affect the total mass emitted before the covering and the amount still available to be emitted over time.

Design Calculations

Using equation 1 (see "Ventilation and Other Factors" on page 5) and equations 2 and 3 (below), it is possible to predict concentrations from emissions data or calculate an allowable emission or required ventilation based on a target concentration. In spite of all the inherent problems, there have been several successful attempts using various sources of emissions data. For example, Black *et al.* (1991) measured emissions from a carpet system in an environmental chamber and in an actual building installation. The predicted concentrations based on the chamber measurements were in close agreement with the field data. In a very different type of situation, Hodgson *et al.* (1991) measured concentrations of an organic solvent used in liquid-process photocopiers and plotters and found good agreement with predictions based on the ventilation rate and the average usage rate of the solvent. Hodgson also measured carpet emissions in a chamber and in a residence and found good agreement (Hodgson *et al.*, 1992).

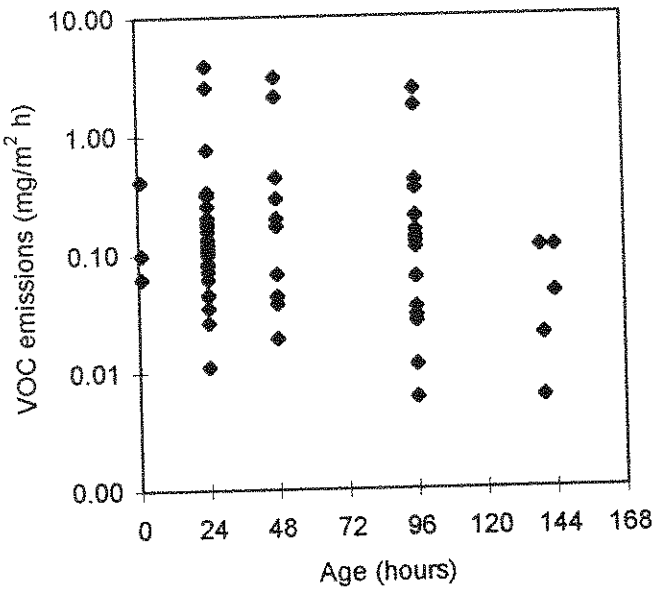

Figure 12 - Carpet emissions from various carpets by age of carpet.

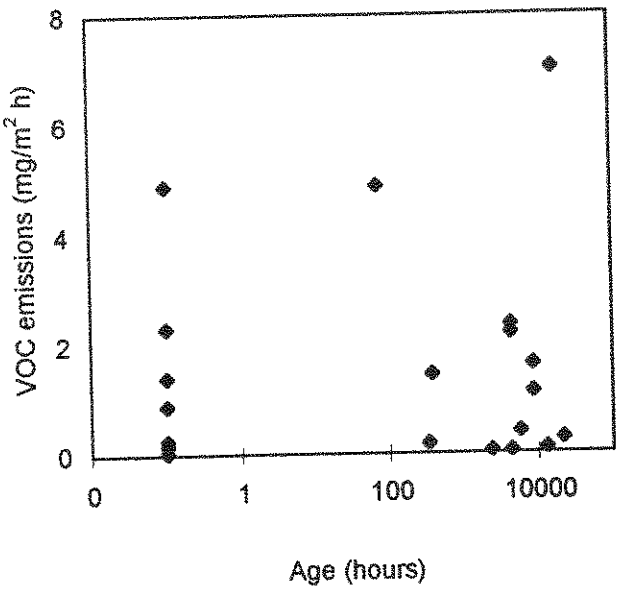

Figure 13 - VOC emissions from various resilient floor coverings by age of covering.

Several equations can be used based on ASTM Standard D5116-90 (ASTM, 1994). For a constant emission rate, the following equation is used. Ignoring sinks, equation (1) can be used.

$$EF=C(N/L) \quad [2]$$

where:

N = chamber air exchange rate, h^{-1}

L = chamber loading, m^2/m^3

For a decreasing emission rate, ignoring sinks, the following equation is used:

$$R = Roe^{-kt} \quad [3]$$

where:

R = emission factor at time, t, $mg/m^2 \cdot h$

Ro = initial emission factor, $mg/m^2 \cdot h$

k = first order rate constant, h^{-1}, and

t = time, h.

Use of Emission Test Data

For a variety of reasons, there is a risk that entirely too much faith is placed in emission test results. Several factors related to the test specimens, the test conditions, and the building conditions to which the test data are applied affect the interpretation and use of indoor source emissions test data. These factors include the following:

- Product/material age and history of environmental exposure
- Air exchange rate
- Temperature
- Air flow at surface
- Material thickness
- Material density
- Material surface characteristics
- Material influence on sink effects, adsorption, and desorption.

Standardized test methods can reduce the uncertainty and variability associated with emissions testing. Such protocols exist for few products. However, work is progressing on developing such protocols, and, in the next few years, many products will be tested using standardized methods. Meanwhile, it is important to request complete information on the product being tested, and the test protocols, methods, and conditions in order to better interpret reported test results. Many manufacturers have tested their products, and those who have are more likely to have addressed strong emission sources or particularly toxic or noxious specific compounds emitted from their products.

Models developed to run on personal computers can calculate concentrations based on emissions test data and ventilation rates. These include "Exposure" developed by Les Sparks at the USEPA and "CONTAM," developed at NIST. They are at various levels of detail and development, and some continue to be developed.

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Trends

Integrated Approach Expands Scope of IAQ

IAQ researchers and professionals are expanding the scope of their work. Issues of increasing interest include energy, ventilation, and general environmental concerns. This trend was clearly evident in four recent major international indoor air meetings in Hungary, Australia, Canada, and Italy. All four meetings included papers and workshops that covered not only IAQ but also energy conservation and broader environmental issues. Organizers of the conferences emphasized the integration of these concerns.

The Australian conference, held in November, 1994, reflected the integration concept in its name: "Indoor Air: An Integrated Approach." In the conference, held on the Gold Coast in Queensland, northeast Australia, one of the targets of integration was radon and other familiar indoor air concerns such as VOCs, microbes, and ventilation. The post-conference report made much of the breadth of the scope and the extent of the integration of concerns related to indoor air not traditionally considered part of IAQ research and professional activities.

At "Healthy Buildings '94" In Budapest in August, 1994, energy conservation and economic concerns played far larger roles than in most past IAQ conferences. This was due, at least in part, to the participation of Hungarians and others from less-developed nations who had previously not been prominent at international meetings of the established "indoor air community." Integration was again mentioned often by organizers and others as an important characteristic and accomplishment of the conference.

A very successful recent conference, held in Montreal in May, was the Second International Conference on "Indoor Air Quality, Energy Conservation, and Ventilation." The organizers explicitly promoted the integration theme and the last two plenary sessions and related poster sessions were focused on it. Again, at the close of the meeting, organizers pointed out the degree of success achieved in the integration of the three topic concerns. Christien Cochet from France, named chair of the 3rd International Conference in this series (to be held June, 1998, in Paris) promised to continue the integration theme in the next meeting.

Many papers presented at the Montreal meeting reached beyond the three topics and the indoor environment to address larger environmental issues. And, the expansion of the conference themes is a reflection of what indoor air researchers and practitioners are encountering in their work. For example, a Canadian federal government study examined the cost effectiveness of potential regulations to require heat recovery ventilation systems in residences. The study evaluated the potential cost effectiveness of such devices in each of Canada's 10 provinces. The report concluded that such devices were cost effective in the colder climates, but not as likely to be so in the mild ones such as British Columbia.

It was reported that the Province of Manitoba asked the researchers to include a 10% surcharge on energy costs in the economic analysis in order to reflect the "external" costs of energy consumption. "Externalities" refers to the environmental costs such as air pollution, energy resource depletion, global warming, and ozone depletion. The ***BULLETIN*** learned that discussions with the all the Canadian provincial representatives included the possibility of applying some cost penalty to reflect externalities in the calculation of energy costs. We believe it likely that in the future, analyses of this sort will either voluntarily impose such penalties (as did Manitoba) for the external environmental impacts or that regulations may impose such requirements. It is also likely that the penalty will be far greater than 10% in order to reflect more accurately the true costs of the environmental externalities. A study in New York State (not reported at the Montreal conference) estimated the cost of externalities as equal to the cost of the energy itself. Thus, including the external costs would effectively double the price consumers pay.

Finally, at Healthy Buildings '95, held last September in Milan, Italy, several papers addressed global, regional, and local environmental issues as well as indoor environment issues. We presented a keynote lecture to begin the conference in which a health building was defined as one that harmed neither the occupants nor the larger environment.

Another aspect of the trend toward broader issue integration includes attention to noise, lighting, and other indoor environmental concerns. Researchers and professionals have learned that building occupant health and comfort problems are not exclusively attributable to air quality problems. Noise, lighting, and other environmental conditions may be important co-factors in many of the problems usually blamed on poor IAQ.

Larger Trend?

The enthusiastic acceptance of these conference themes indicates that there has been a latent need for this broader view that integrates indoor and general environmental concerns. In the time (since 1978) that we have been involved in indoor environment issues, we have observed a trend toward recognizing the interconnectedness of various aspects of the indoor environment. The acceptance of building-related health and comfort problems as "multifactorial" has increased, although there certainly are many indications of a continued search for overly simplified causes.

In Europe this trend is particular strong. The Netherlands appears to be leading the world in planning for sustainable technologies, and this is manifested in many building-related activities throughout the country.

Meanwhile, in our own consulting, more and more clients are asking for advice on designing more environmentally responsible buildings. Some call it "sustainable design" or "green buildings," among other things. The increasing use of these labels clearly reflects the willingness of building owners and developers to pay at least some attention to the broad environmental impacts of their buildings. This is affecting designers and researchers and may be one of the forces leading indoor environment researchers directly to expand the scope of their work to include related issues.

There has long been an interest in the energy consequences of IAQ control, especially since so much of it involves ventilation system construction and operating costs. But the concern about energy in the past has been driven by the economic cost. Now, more designers and their clients are focusing on the environmental consequences of energy consumption — the depletion of resources, the emissions of contaminants during the combustion of fossil fuels, global warming due to CO_2 and other "greenhouse" gases, and stratospheric ozone layer depletion due to the use of certain refrigerants. Energy conservation measures that use foams created by certain blowing agents are also a concern if the agents are known ozone-depleting compounds.

Proceedings are available for each of the conferences; see the References below.

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Publications

"Indoor Air Quality in Office Buildings: A Technical Guide"

Scores of publications provide guidance on office environments: how to design, operate, evaluate, investigate, and study them. But few adequatel.y describe common, practical measurement methods and the criteria necessary for evaluating the results. In 1990, the Danish Building Research Institute (Statens Byggeforskningsinstitut) produced a highly valuable monograph "Indoor Climate and Air Quality Problems: Investigation and Remedy" (SBI Report 212). Now, from Canada, comes a similarly valuable report, and it's even backed by the national and provincial governments.

The Canadian guide states that its purpose is to "...provide guidance for those people responsible for conducting indoor air quality (IAQ) investigations in office buildings. It will assist them in determining the cause of poor IAQ, in establishing at what point specific professional services are required, and in defining the methodology and scope of a particular IAQ study."

A remarkable amount of information is packed into its 55 half-sized pages. Background on SBS, guidance on ventilation and ventilation systems, and, most unique to this publication, measurement methods useful in evaluating IAQ.

Written by Tedd Nathanson, an engineer with Health Canada, the report was prepared under the direction of the Federal Provincial Working Group on Indoor Air Quality in the Office Environment. It is remarkable that the detailed guidance Nathanson provides made it through the approval process of both the Canadian national and the provincial authorities involved in its review.

Reference

Indoor Air Quality in Office Buildings: A Technical Guide, A Report of the Federal-Provincial Advisory Committee on Environmental and Occupational Health. Copies of the report are available at no cost from Communications Branch, Health Canada, Tunney's Pasture, Ottawa, Ontario K1A0K9, 613 954 5995, Fax 613 952 7266.

Copies of the Danish Building Research Institute report are available from SBI, P. O. Box 119, DK-2970 Hørsholm, +45 42 86 55 33, Fax +45 42 86 75 35. Cost is DKK 100.

Publications

"Indoor Air Quality: A Comprehensive Reference Book"

The title says it all. The 1,049 pages in this tome cover the entire range of IAQ issues. Marco Maroni of Italy assembled a horde of experts to write the book and, together with Bernd Seifert (Germany) and Thomas Lindvall (Sweden), edited the most comprehensive treatment of IAQ published between two covers. With the sponsorship and participation of many of the most important national and international institutions involved in IAQ, the three Europeans IAQ leaders have achieved a monumental task.

There certainly is not a consistent level of depth in the treatment of various topics. The availability and willingness of contributors dictated the coverage. However, if you are looking for a single volume that contains the most complete text on all IAQ topics, this book is for you. It was intended to satisfy the needs of indoor air students and professionals from medical doctors to engineers, from industrial hygienists to architects, from chemists to physicists.

Reference

M. Maroni, B. Seifert, and T. Lindvall (eds.) 1995. Indoor Air Quality: A Comprehensive Reference Book (Air Quality Monographs, Volume 3). Amsterdam: Elsevier Science B.V. To obtain a copy, contact Elsevier Science, P. O. Box 1991, 100 BZ Amsterdam, The Netherlands. +31 20 5862 911, Fax +31 20 5862 623.

Publications

"Health Implications of Fungi in Indoor Environments"

Another definitive volume has emerged from Elsevier Science, this one edited by six European experts on microbiology. Its pages contain contributions from over 80 international experts on microfungi with a focus on indoor air. The book grew out of a workshop held November 1992 in the Netherlands.

Topics include everything to do with fungi indoors including detection, indoor ecology, symptoms, and prevention. The overview, written by Brian Flannigan (Scotland) and J. David Miller (Canada), establishes the state of the art and suggests potential directions for the field. The recommendations at the end of the book suggest substantial amounts of important work remain to be done on the problems of indoor fungi. Among the conclusions is recognition that "...there is no ideal method for sampling of fungal particles in indoor air available." While the nature of mycoflora indoors is known, especially for temperate climates, more research is needed for subtropical and tropical climate zones.

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Calendar of IAQ Events

March 4-6, 1996. **Building Energy,** Copley Plaza Hotel, Boston, Massachusetts. Organized by Northeast Sustainable Energy Association. Contact: NESEA, 50 Miles Street, Greenfield, MA 01301, 413 774 6051.

March 17-22, 1996. **1996 Affordable Comfort Conference,** Palmer House Hilton, Chicago, Illinois. Sponsored by Affordable Comfort, Inc. Contact: Affordable Comfort 96, P. O. Box 9367, Pittsburgh, PA 15225, Fax 412 299 1137. *For more information, contact Linda Wigington, 412 852 3085.*

March 27-29, 1996. **Biological Contamination of Indoor Environments,** San Diego, California. Sponsored by US EPA Region 9. Contact: MidAtlantic Environmental Hygiene Resource Center, 3624 Market Street, First Floor East, Philadelphia, PA 19104, 215 387 2255, Fax 215 387 6321. *Topics include Biology of Biocontamination, Public Health Issues and Risks, Health Effects, Legal and Liability Issues, Investigating Biocontamination Problems, Control and Prevention, and Remediation. Registration fee is $695, $350 for state and local governments, schools, colleges, and universities.*

April 16-18, 1996. **ASTM Subcommittee D22.05 on Indoor Air, Spring Meeting**. Omni Rosen Hotel, Orlando, Florida. Contact: George Luciw, ASTM Staff Manager, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, 610 832 9710, Fax 610 832 9666. *The subcommittee will be considering results of ballots on placement and use of passive monitors, inspection of water systems and investigating possible outbreaks of Legionellosis, test method for nicotine in indoor air, and estimating contribution of environmental tobacco smoke to respirable suspended particles based on UVPM and FPM. There will be a workshop on Carbon Monoxide detectors organized by Niren Nagda (301 540 1300, Fax 301 540 6924). There is no charge for attendance at the meeting and membership is not required to participate.*

April 22-23, 1996. **Diagnosing and Mitigating Indoor Air Quality Problems.** San Francisco, Sponsored by Indoor Environmental Engineering (IEE). Contact: IEE, 1448 Pine Street, Suite 103, San Francisco, CA 94109, 415 567 7700, Fax 415 567 7763. *Instructor is Francis J. "Bud" Offermann PE, CIH. Course fee is $4795 ($695 for ASHRAE, ABIH, AIHA, and BOMA members).*

June 22-26, 1996. **ASHRAE Annual Meeting**, San Antonio, Texas. Contact: ASHRAE Meetings Department, 1791 Tullie Circle NE, Atlanta, GA 30329, 404 636 8400, Fax 404 321 5478.

July 7-11, 1996. **Indoor Air Quality: Critical Evaluation of the Science and the Art**, Johnson State College, Johnson, Vermont, sponsored by ASTM. Contact George Luciw, ASTM Staff Manager, 610 832 9710.

International Events

April 21-24, 1996. **Buildings for Healthy Living,** Czech Republic International Conference, Praha Hotel, Prague, Czech Republic. Contact: Dr. Ivana Holcátová, Institute of Hygiene & Epidemiology, 1st Faculty of Medicine, Charles University, Studnickova 7, 128 00 Prague 2, Czech Republic. *The official language of the conference is English. Registration fee is US$400 ($350 for ISIAQ members). There are several post-conference tours available in and around Prague.*

July 17-19, 1996. **Roomvent '96, The 5th International Conference on Air Distribution in Rooms,** Yokohama, Japan. Contact: Dr. S. Kato, Murakami and Kato Laboratory, Institute of Industrial Science, University of Tokyo, 7-22-1 Ropponi, Minato-ku, Tokyo 106, Japan, +81 3 3402 6231 ext 2575, Fax +81 3 3746 1449.

July 21-26,1996. **Indoor Air '96, The 7th International Conference on Indoor Air Quality and Climate**, Nagoya, Japan. Contact: Dr. Koichi Ikeda, Secretary, Indoor Air '96, The Institute of Public Health, 6-1, Shirokanedai 4-chome, Minato-ku, Tokyo 108, Japan, +81 3 3441 7111 ext 275, Fax +81 3 3446 4723. *Papers are due March 31, 1996. This is the "big" triennial indoor air conference. It should be particularly interesting with a large amount of information from the Asian indoor environment research community. Concerns about high costs for travel to Japan appear contradicted by the conference announcement which indicates that living expenses in Nagoya should not be much different from those found in most European and North American major cities.*

August 17-21, 1996. **Environmental Exposures, Risks and Values: Setting Priorities in Epidemiology,** International Society for Environmental Exposure (ISEE), University of Alberta, Edmonton, Alberta, Canada. Contact Dr. Colin L. Soskoine, Epidemiology Program, Univ. of Alberta, 13-103 Clinical Sciences Building, Edmonton, Alberta, Canada, T6G 2G3, 403 492 6013, Fax 403 492 0364. *Contact Dr. Soskoine to receive the Announcement.*

August 25-30, 1996. **3rd NIVA Course on The Sick Building Syndrome**, Schæffergården, Charlottenlund (Copenhagen), Denmark. Contact: Gunilla Ahlberg, Course Secretary, NIVA, Topeliuksenkatu 41 a A, FIN-00250 Helsinki, Finland, +358 0 474 7498, Fax +358 0 474 7497. *Course fee is FIM 2000 and participation is limited to 40 students. This has been one of the most outstanding indoor air programs in the past due to a large number of expert faculty members and a great deal of discussion among faculty and between faculty and students. The conference center is also one of the finest. Some scholarships are available.*

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