

**PART II. CHEMICAL AND PHYSICAL CHARACTERIZATION**

**Characterizing Material Sources  
and Sinks**

**Current Approaches**

BRUCE A. TICHENOR

*Indoor Air Branch  
Air and Energy Engineering Research Laboratory  
U.S. Environmental Protection Agency  
Research Triangle Park, North Carolina 27711*

**INTRODUCTION**

The purpose of this paper is to review and discuss the approaches currently used by indoor air quality (IAQ) researchers and practitioners to characterize the chemical emissions from indoor materials, including the interaction of these emissions with indoor sinks. Although the immediate objective of such approaches is the development of source emission rates and sink adsorption/desorption rates, the ultimate goal is to relate the source emissions to human health and comfort. If the link between indoor sources and effects on occupants can be established, then guidance can be provided to ensure that materials selected for use indoors are compatible with good IAQ.<sup>a</sup>

**MATERIAL SOURCES AND SINKS OF INTEREST**

There are myriad sources of indoor air pollution, including building materials, furnishings, consumer products, combustion (for example, environmental tobacco smoke (ETS), cooking, heating appliances), and outdoor air. This paper will focus on building materials and furnishings.

***Dry Materials***

Dry materials, which include the majority of materials used to construct and furnish residential and commercial environments, are characterized by relatively low emission rates which decay slowly. Such materials include wood products, floor coverings (carpet, vinyl), wall coverings (wallpaper, fabric), ceiling materials (acoustic tiles, "blown" gypsum), and insulation (fiberglass, rigid foam). Heating, ventilating, and air conditioning (HVAC) systems also include potential indoor air pollution sources, such as duct liners. Furnishings, composed of pressed wood products and/or upholstery, are additional potential sources.

<sup>a</sup> The IAQ literature is a rich resource, and references are cited to direct the reader to publications that furnish additional details. Because the topics covered in this paper are very broad, no attempt was made to cite *all* relevant references. The reader is encouraged to review other information sources if more comprehensive coverage of individual topics is desired.

### *Wet Materials*

Modern construction techniques rely heavily on a wide variety of architectural coatings (paints, stains, varnishes), adhesives, caulks, and sealants. Such materials are applied "wet," and their emissions (mostly petroleum based solvents) are relatively high and decay rapidly.

### *Sinks*

Indoor surfaces act as sinks by adsorbing and later reemitting vapor-phase organic indoor air pollutants. As shown later in this paper, indoor sinks play a major role in determining the concentration-versus-time history associated with indoor sources, especially wet sources. Indoor sinks of interest include floors (particularly carpets and rugs), walls, ceilings, HVAC systems (including supply and return ducts and filters), and furnishings.

## FACTORS TO BE CONSIDERED

In developing and using methods for determining the behavior of indoor sources and sinks, it is important to consider the governing physical and chemical processes, as well as the important variables impacting these processes.

### *Mass Transfer Processes*

Mass transfer processes controlling the emissions of vapor-phase organics from indoor materials and sink interactions include evaporation, adsorption, absorption, diffusion, and convection. Each of these mechanisms is discussed below. Detailed descriptions are available in appropriate references.<sup>1,2</sup>

#### *Evaporation*

Evaporation is the predominant mechanism controlling initial emissions from wet materials. The evaporative mass transfer of a given organic compound from the surface of an indoor material to the indoor environment can be expressed as

$$E = k_m(VP_s - VP_a) \quad (1)$$

where  $E$  is the evaporative emission rate (mg/hr);  $k_m$  is the mass transfer coefficient (mg/mm Hg-hr);  $VP_s$  is the compound vapor pressure at the surface of the material (mm Hg); and  $VP_a$  is the compound vapor pressure in the air above the surface (mm Hg). Because the vapor pressure is directly related to the concentration, the evaporative emission rate is proportional to the difference in concentration between the surface and the overlying air.

#### *Adsorption*

Mass transfer to and from indoor sinks is primarily governed by adsorption and desorption processes. Several well-known adsorption isotherm theories (for

example, Langmuir, Freundlich, and Brunauer-Emmett-Teller) have been developed to describe the adsorptive/desorptive behavior of gas molecules with solid surfaces. IAQ researchers have begun to apply these theories to the behavior of indoor sinks.<sup>3,4</sup> The most fundamental theory is the Langmuir isotherm, which can be expressed as

$$k_a C_a = k_d M_e \quad (2)$$

where  $k_a$  is the adsorption rate constant (m/hr);  $C_e$  is the equilibrium vapor-phase concentration (mg/m<sup>3</sup>);  $k_d$  is the desorption rate constant (hr<sup>-1</sup>); and  $M_e$  is the equilibrium mass on the sink (mg/m<sup>2</sup>). Thus, based on the Langmuir theory, the rate of adsorption is proportional to the vapor-phase concentration, and the rate of desorption is proportional to the mass on the sink.

#### *Absorption*

Mass transfer to sinks by absorption (for example, for a water-soluble compound to a moist surface) is another possible mechanism of interest. The importance of this process for indoor sources and sinks has not yet been determined.

#### *Diffusion*

Diffusion plays a major role in source emissions and sink interactions. After a molecule is released from a source or sink by evaporation or desorption, diffusion through the boundary layer occurs. The rate of diffusion is controlled by the compound's diffusion coefficient, the level of turbulence, and the thickness of the boundary layer. In addition, diffusion within the source (or sink) may be important (that is, the molecule must migrate by diffusion to the surface).

#### *Convection*

Convective mass transfer is the bulk flow of air away from the surface of the boundary layer. This process provides a means for transporting the indoor pollutants to the bulk air and contributes to in-room mixing.

### *Environmental Variables*

Among the important environmental variables that impact material source emissions and sink behavior are temperature, humidity, air exchange rate, velocity, and turbulence.

#### *Temperature*

Temperature affects the vapor pressures, adsorption and desorption rate constants, and diffusion rates of organic vapors. In all cases, increases in temperature cause increases in the mass transfer rates for the processes affected by these parameters.



### *Humidity*

Humidity has been shown to affect the emission rate of formaldehyde from pressed wood products and may have similar effects for other water soluble gasses.

### *Air Exchange Rate*

Air exchange rate, expressed in air changes per hour (ACH), is defined as the volume of outdoor air that enters (and leaves) the indoor environment in 1 hr divided by the volume of the indoor space. It may occur via mechanical ventilation systems or by infiltration/exfiltration. The air exchange rate determines the amount of dilution and flushing that occurs in indoor environments. The higher the rate, the greater the dilution and the lower the indoor concentration. Thus, the air exchange rate can impact evaporative emission rates and the mass adsorbed on indoor sinks.

### *Velocity and Turbulence*

Mass transfer from surfaces is affected by the velocity in the boundary layer above the surface and by the level of turbulence. Generally, the higher the velocity and level of turbulence, the faster the mass transfer. In a practical sense, above a certain velocity and level of turbulence, the resistance to mass transfer in the boundary layer is minimized (that is, the mass transfer coefficient reaches its maximum value).

### *Material Characteristics/Composition*

The characteristics and composition of indoor materials have a major impact on their emissions and sink behavior. The number and types of chemicals emitted are of obvious importance. Many of the chemicals' properties (vapor pressure, diffusion coefficients, molecular weight and size) affect their emission characteristics. For sink materials, the type of material and type of surface (smooth, rough, fleecy) are significant. Finally, the amount (surface area, mass) of material used will clearly affect the total mass emitted from sources and the total mass adsorbed on and desorbed from sinks.

## **SOURCE TESTING METHODS—CHEMICAL EMISSIONS**

A variety of methods are used by IAQ investigators to determine the chemical emissions from indoor materials and furnishings. TABLE 1 summarizes the methods, and the following discussion briefly describes each method. Each of these methods requires the use of appropriate techniques for sampling (for example, syringe, canister, and sorbent techniques) and analysis (for example, gas chromatography—GC) of the organic chemicals of interest. Because the focus of this paper is on the overall methods of characterizing indoor sources and sinks, only brief discussions of these sampling and analysis techniques are provided. The reader is encouraged to consult the cited references for more details.

### *Laboratory Studies*

Relatively simple laboratory studies can be conducted to determine material composition and emissions composition.

#### *Extraction*

Solvent extraction (for example, using methylene chloride) of dry indoor materials can furnish information on the organic chemicals contained in the material.

TABLE 1. Source Testing Methods—Chemical Emissions

<b>LABORATORY STUDIES</b>	
<i>Extraction and Direct Analysis</i>	
<ul style="list-style-type: none"> <li>– Provide information on material composition</li> <li>– Do not provide emissions composition or emissions rate data</li> </ul>	
<i>Static Headspace</i>	
<ul style="list-style-type: none"> <li>– Provide information on emissions composition</li> <li>– Do not provide emissions rate data</li> </ul>	
<b>DYNAMIC CHAMBER STUDIES</b>	
<i>Small Chambers</i>	
<ul style="list-style-type: none"> <li>– Provide emissions composition and emissions rate data under controlled environmental conditions</li> <li>– Chamber size may limit use for some material sources (for example, furniture, work stations)</li> </ul>	
<i>Large Chambers</i>	
<ul style="list-style-type: none"> <li>– Provide emissions composition and emissions rate data under controlled environmental conditions</li> <li>– Large chambers may be required for evaluating emissions during the application phase of wet materials</li> </ul>	
<b>FULL-SCALE STUDIES</b>	
<i>Test Houses</i>	
<ul style="list-style-type: none"> <li>– Provide emissions composition and emissions rate data under "semi-controlled" environmental conditions; sink factors must be considered</li> <li>– Very useful for validating chamber emissions test results obtained under IAQ models</li> </ul>	
<i>Field Studies</i>	
<ul style="list-style-type: none"> <li>– Provide integrated emissions profile of all sources and reemitting sinks under uncontrolled conditions</li> <li>– Emission rate determinations are generally not possible</li> <li>– Differentiating between source and sink emissions is extremely difficult</li> </ul>	

Analysis of the extract by GC with mass spectrometry will identify the compounds, including the nonvolatile and semivolatile species. Such techniques have been used to evaluate the composition of carpet samples.<sup>5</sup>

#### *Direct Analysis*

Some wet products (for example, paints and other coatings) can be analyzed to determine their composition. Techniques are available for determining the mass



of total volatile organic compounds (VOCs) or individual compounds per volume of coating. Generally, these techniques involve 1) evaporation to dryness or 2) dilution followed by GC analysis. Environmental Protection Agency (EPA) Reference Method 24 and associated American Society for Testing and Materials (ASTM) methods are examples of such techniques.<sup>6</sup>

#### *Static Headspace*

The composition of emissions from indoor materials can often be determined via a static headspace analysis.<sup>7</sup> In this procedure, a sample of material is placed in a small (for example, 1 liter), airtight container lined with inert material. Samples of the air inside the container (that is, headspace) are analyzed to determine the compounds emitted by the material. Static headspace analyses are normally conducted at ambient temperature (for example, 23°C) and atmospheric pressure. In some cases, investigators use higher temperatures to increase the emission rate to ensure a high enough concentration to analyze. Also, inert gas, flow-through headspace analyses may be conducted on low-emitting materials (for example, carpet) to provide an increased sample size.<sup>5</sup>

#### *Dynamic Chamber Studies*

In order to determine the impact of indoor sources on IAQ, information on the source emission rate is required. Such information can be obtained only via dynamic, flow-through testing. Both small and large chambers are commonly used to conduct such testing.

#### *Small Chambers*

Small (<5 m<sup>3</sup>) environmental test chambers are used throughout the world to evaluate emissions from indoor materials.<sup>8-11</sup> A typical small chamber facility includes a clean air delivery system, one or more test chambers (well-mixed and built with nonadsorbent interiors), environmental controls (temperature, humidity, air flow rate), and sampling and analysis equipment. Emissions testing is conducted by placing a sample in the chamber and measuring the concentration (individual compounds or total organics) at the chamber outlet. The sample size is usually determined by the "loading factor" (that is, the ratio of the test specimen area to the chamber volume). Generally, the loading factor would be set equal to the surface area to volume ratio one would expect for normal use of the material in full-scale environments. Concentration data are collected over a sufficient time interval to adequately describe the time history of the emission rate (see below). Although small chamber testing methods are still being improved, the technology has matured enough to result in an ASTM Standard Guide.<sup>12</sup> In addition, the Commission of the European Communities has approved the issuance of a Guideline for the Characterization of Volatile Organic Compounds Emission from Indoor Materials and Products Using Small Test Chambers.

Small chambers have obvious limitations. Normally, only samples of larger materials (for example, carpet) can be tested. Small chambers may not be applicable for testing complete assemblages (for example, furniture, work stations). For some materials, small chamber testing may provide only a portion of the emission profile of interest. For example, the rate of emissions from the application of paints

and coatings, via brushing, spraying, or rolling, is higher than the rate during the drying process. Small chamber testing cannot be used to evaluate the application phase of the coating process.

#### *Large Chambers*

Large, room-sized (for example, 15–30 m<sup>3</sup>) chambers are used to overcome the limitations of small chambers noted above.<sup>11,13,14</sup> As with small chamber testing, careful control of the environmental variables is necessary to ensure accurate results from large chamber testing. Emissions testing procedures using large chambers are essentially the same as with small chambers, except in large chambers the sample is usually collected at one or more locations in the chamber instead of in the outlet flow.

#### *Full-Scale Studies*

Although dynamic chamber studies are useful for determining emission rates of indoor materials under controlled conditions, full-scale test house and/or field studies are necessary to validate the chamber data. Full-scale studies also provide the opportunity to evaluate the interaction of source emissions with indoor sinks. In addition, evaluation of such factors as variable air exchange rates, operation of heating/cooling systems, room-to-room air movement, and occupant activities is possible with full-scale studies.

#### *Test Houses*

IAQ test houses are used to investigate a variety of indoor air pollution research questions, including the behavior of sources and sinks.<sup>14,15</sup> Test houses are generally unoccupied and are provided with instruments and equipment for monitoring a variety of variables, including temperature, humidity, air exchange rate, and operation of the heating/cooling system. Systems are installed to allow indoor air samples to be collected at various locations within the house. Both on-site and off-site analytical instruments are used to quantify indoor pollutant levels. IAQ test houses are generally single-family residences, with construction features typical of the area where they are located. Because they are unoccupied, test houses can be used to investigate the behavior of single sources without the confounding effects of occupant activities. Unlike chamber studies, precise control of the environmental variables is difficult, especially the air exchange rate, which is controlled by the weather. In addition, the multitude and complexity of interior surfaces make it imperative that the interaction of sources and sinks be considered during data analysis. Consideration must also be given to the pollutant levels in the outdoor air and the background levels in the test house prior to any experiments. In spite of these complications, IAQ test houses are extremely valuable research tools for investigating sources and sinks in a realistic manner.

#### *Field Studies*

Literally hundreds of field studies have been conducted to investigate indoor air pollution problems. Field studies often provide insight into the “source” of the



IAQ problem. For example, finding excessive levels of a compound associated with a specific source (for example, paradichlorobenzene from moth repellent) can enable the source to be identified. Unfortunately, many indoor sources (for example, solvent-containing products) share common emission profiles in terms of the compounds emitted. Thus, isolating the source of a common indoor pollutant based on indoor measurements may be impossible. In addition, reemissions from indoor sinks can cause elevated indoor concentrations of some pollutants to exist long after the original source of the pollutant has been depleted. Thus, field study results generally provide an integrated assessment of IAQ based on the emissions from a multitude of sources and reemitting sinks under uncontrolled conditions, and using field study results to determine the emission rates of individual sources is extremely difficult if not impossible.

### EVALUATION OF INDOOR SINKS

Methods used evaluate indoor sinks with respect to their adsorptive and desorptive behavior parallel the source characterizations methods described above. Al-

TABLE 2. Sink Testing Methods—Organic Chemicals

<b>PACKED COLUMNS</b>
– Provide data on mass adsorbed but not on adsorption and desorption rates
– Only applicable to high surface area material (for example, carpet fibers)
<b>DYNAMIC CHAMBER TESTS</b>
– Provide data on mass adsorbed and rates of adsorption and desorption under controlled environmental conditions
<b>TEST HOUSE STUDIES</b>
– Provide data on rates of adsorption and desorption under "semi-controlled" environmental conditions for multiple sink materials
– Useful for validating dynamic chamber sink results using IAQ models

though researchers have been investigating "sink effects" for several years,<sup>16</sup> only a few of these investigations have focused on determining the rate constants of interest. TABLE 2 summarizes the sink testing methods used at present. Brief descriptions of these methods, with emphasis on vapor-phase organic compounds, follow.

#### *Packed Columns*

The principles of gas/solid chromatography have been used to evaluate the sink characteristics of indoor materials.<sup>3</sup> In this technique, samples of material (for example, fibers) are packed into columns and the retention times of the organic compounds are determined at various temperatures. The retention times are related to the partition coefficients, which represent the equilibrium mass adsorbed on the material being tested. This method furnishes information on the equilibrium



conditions, but does not provide kinetic data on the adsorption or desorption rates. In addition, the method is limited to the testing of high surface area materials, such as carpet or upholstery fibers. The method is not applicable to the evaluation of such indoor surfaces as wallboard because the material would have to be finely divided prior to being packed in the column. Even complete carpets, including fiber, backing, and bonding adhesive, could not be adequately evaluated with this method.

#### *Dynamic Chamber Tests*

Dynamic flow-through chambers can be used to evaluate the sink rates (adsorption/desorption) for indoor surfaces.<sup>17,18</sup> Samples of the sink material are placed in chambers and exposed to known concentrations of pollutants. As with source testing, concentration-versus-time data are collected. These data are then analyzed, using appropriate sink models, to determine the mass adsorbed and the adsorption and desorption rates (see below).

#### *Test House Studies*

IAQ test house studies can be used to evaluate the validity of chamber-derived adsorption and desorption sink rates.<sup>18</sup> Concentration-versus-time data collected in test house studies are evaluated using IAQ models containing equations describing the sink behavior. To date, such experiments have been only partially successful in validating dynamic chamber sink results.

### ANALYSIS OF DYNAMIC CHAMBER TEST RESULTS

As noted above, dynamic chamber testing is the most common method being used to determine 1) source emission rates, 2) mass adsorbed on sinks, and 3) sink adsorption and desorption rates. Computational techniques have been developed to analyze dynamic chamber test data to produce source and sink rates.

#### *Source Evaluations*

Source emission factors are determined by fitting appropriate source models to chamber concentration-versus-time data. The model selected is based on the source behavior.

For sources with constant emission rates, the calculation of the source emission factor is straightforward, as indicated by

$$EF = C(N/L) \quad (3)$$

where  $EF$  is the emission factor ( $\text{mg}/\text{m}^2\text{-hr}$ );  $C$  is the chamber concentration at equilibrium ( $\text{mg}/\text{m}^3$ );  $N$  is the chamber air exchange rate ( $\text{hr}^{-1}$ ); and  $L$  is the chamber loading value ( $\text{m}^2/\text{m}^3$ ).

For sources with decaying emissions, a common approach is to assume a first-order decay,<sup>10</sup> as indicated by

$$EF = EF_0 e^{-kt} \quad (4)$$

where  $EF_0$  is the initial emission factor ( $\text{mg}/\text{m}^2\text{-hr}$ );  $k$  is the first-order rate constant ( $\text{hr}^{-1}$ ); and  $t$  is the time ( $\text{hr}$ ). Another approach for some sources is to assume two first-order rate constants.<sup>9</sup> Source models have also been developed that account for chamber sink effects and the effect of vapor pressure on emissions.<sup>19</sup>

### *Sink Evaluations*

Methods for determining sink characteristics (that is, mass adsorbed, adsorption and desorption rates) from dynamic chamber test data are not as well developed as the source evaluation methods. One approach uses two chambers: one with sink material, the other empty.<sup>17</sup> Ratios of the concentrations from the two chambers are analyzed (first-order processes, are assumed), to obtain empirical equations for adsorption and desorption. Another approach uses a single chamber and fits the concentration-versus-time data using models based on adsorption/desorption theory (for example, Langmuir isotherms).<sup>18</sup> This approach provides adsorption and desorption rate constants. Both approaches provide estimates of mass adsorbed by calculating the difference between "sink" and "no sink" concentration-versus-time profiles.

## USING THE RESULTS OF SOURCE/SINK EVALUATIONS

As discussed above, methods are available for determining the chemical emission rates of indoor sources and sink adsorption/desorption rates. This information is used in IAQ models to predict indoor concentrations and occupant exposure. The source/sink data can also be used to provide guidance on selecting indoor materials.

### *Predict Concentration versus Time*

A variety of IAQ models are available.<sup>20</sup> Such models are used to calculate indoor concentrations, in time and space, based on 1) source/sink behavior; 2) time of use, amount, and location of sources; 3) type, area, and location of sinks; 4) outdoor air exchange; 5) number and dimensions of rooms; 6) room-to-room air movements; and 7) HVAC system operation. As discussed above, IAQ test house experimental data can be used with IAQ models to validate the chamber-derived source emission rates and sink adsorption and desorption rates.<sup>15</sup> FIGURE 1 is an example of an IAQ model prediction. The data shown in FIGURE 1 are from an IAQ test house evaluation of wood stain emissions.<sup>18</sup>

Several features of FIGURE 1 merit discussion:

1. IAQ models can accurately predict indoor concentrations if source and sink behavior is well defined and the indoor environment is well characterized. For the example shown in FIGURE 1, source and sink rates were based on



- dynamic chamber tests and the IAQ test house environment was well known, including measurements of outdoor air exchange during the experiment.
2. Indoor sinks can dramatically extend the time of elevated concentrations due to source emissions. The no sink curve in FIGURE 1 shows that the concentration would be reduced to background in less than 100 hr in the absence of reemissions from sinks. The actual data and the model predictions show that the concentrations exceeded background levels for at least 500 hr.
  3. Indoor sources, especially wet sources, can cause vapor-phase organic concentrations well above the levels presumed to cause irritation. In the experiment described by FIGURE 1 (where only 6 m<sup>2</sup> of oak flooring was stained in a house with a volume of 300 m<sup>3</sup>), concentrations of organic vapors reached several hundred mg/m<sup>3</sup>. In another study, concentrations of several thousand mg/m<sup>3</sup> were measured after parquet wood floors were

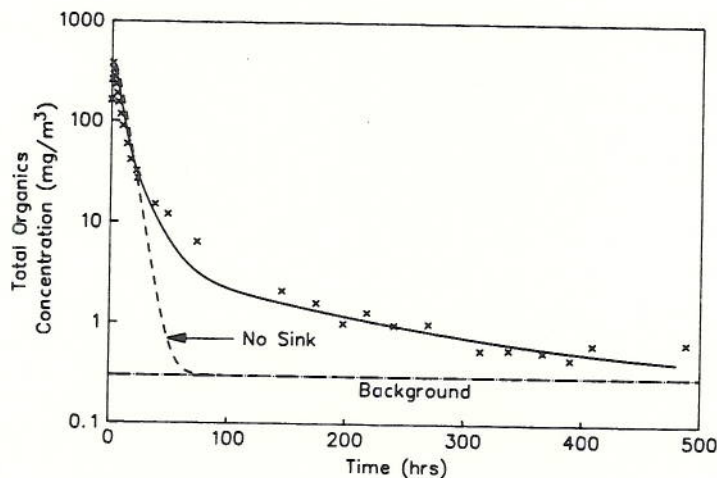


FIGURE 1. IAQ model prediction—test house/wood stain experiment.

- refinished with a two-component polyurethane coating.<sup>21</sup> These concentrations are well above the 3–25 mg/m<sup>3</sup> “discomfort range” and the >25 mg/m<sup>3</sup> “toxic range” recently proposed by Molhave.<sup>22</sup>
4. Vapor-phase organic concentrations from wet sources vary widely over time. As shown in FIGURE 1 and reported by others,<sup>21,23</sup> concentrations can change by several orders of magnitude in hours or days. This time-varying behavior is not consistent with the constant concentration exposures used in evaluating irritation and other human health effects.<sup>24</sup> In addition, even though the concentrations decay over time, they are well in excess of the concentration of total organics (25 mg/m<sup>3</sup>) for periods much longer than the exposure time (2.75 hr) of the human subjects evaluated by Otto and his colleagues.<sup>24</sup> Thus, evaluations of irritation and other effects using human subjects are being conducted at concentrations and exposure times well below those that are caused by the use of common indoor sources of vapor-phase organics.

### *Evaluate Occupant Exposure*

By combining occupant activity patterns with concentration-versus-time profiles, occupant exposure to source emissions can be estimated. The U.S. Environmental Protection Agency has developed such an IAQ exposure model.<sup>25</sup> This exposure model, based on a widely used IAQ model developed for use on a personal computer,<sup>26</sup> can be used to determine both instantaneous and cumulative individual exposure to vapor-phase organic compounds based on inhalation.

## **LINKING BIOLOGICAL RESPONSES TO SOURCE/SINK CHARACTERISTICS**

So far, this paper has discussed methods for determining the emissions characteristics of indoor sources and sinks. Models for determining indoor concentrations and individual exposure by coupling the source/sink behavior to environmental parameters have also been addressed. The next obvious step in the source evaluation process is to link the impact of sources/sinks on IAQ to human health and comfort. In fact, making this link was a central focus of the conference reported in these proceedings, and many of the papers describe the human responses to indoor air pollutants and the methods used to determine these responses. Following is a brief discussion of how indoor sources and sinks might be linked to human health and comfort.

### *Use Available Health Effects Data*

Data on the health effects of many chemicals are available. For example, the Registry of Toxic Effects of Chemical Substances (RTECS) supplies information on thousands of chemicals.<sup>27</sup> Effects such as skin and eye irritation, mutation, reproductive effects, toxicity, and cancer are presented for a variety of exposure scenarios, including inhalation. The data in RTECS are presented for single compounds and are based, for the most part, on animal exposures to constant concentrations.

### *Use Published Guidance*

Several organizations publish guidance on exposure to indoor air pollutants. The American Conference of Governmental Industrial Hygienists (ACGIH) publishes occupational exposure guidance for a number of chemical substances and physical agents.<sup>28</sup> Although the ACGIH guidance is widely used by industrial hygienists, its application to nonindustrial environments is questioned by many in the IAQ research community. Guidance specific to IAQ is available from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE),<sup>29</sup> the World Health Organization (WHO),<sup>30</sup> and the Canadian government.<sup>31</sup> The guidance published by these organizations is for specific chemicals and constant concentrations. Some guidance is provided for dealing with mixtures.<sup>28</sup> Recently, Molhave<sup>22</sup> and Seifert<sup>32</sup> have suggested indoor "limits" for total VOCs.



### *Guidance on Material Selection*

As discussed above, source/sink emission characteristics can be used in IAQ models to predict indoor concentrations. By using guidance on "acceptable" indoor concentrations, Tucker showed how this method could be used to suggest limits on source emissions for various indoor sources for given indoor environments.<sup>33</sup>

### *Source Testing Methods—Biological Responses*

Several factors explain why the use of guidance on indoor concentrations to suggest limits on source emissions provides only an indirect link between these emissions and a biological response:

1. Guidance on indoor concentrations is generally limited to single compounds, whereas indoor source emissions usually involve complex mixtures.
2. Guidance on indoor concentrations is based on averages over a given time interval, whereas most indoor source emissions vary over time (for example, see FIG. 1).
3. Data on many of the endpoints of health effects (for example, sensory irritation) do not exist for a majority of the compounds emitted from many indoor sources.

In order to overcome these limitations, testing methods are needed to directly determine the biological response to source emissions. Such biological response based methods might include, for example, 1) gas-phase bioassays using microorganisms; 2) animal tests for sensory irritation (for example, mouse respiration),<sup>34</sup> inhalation toxicity, and eye and skin irritation; and 3) human evaluations of sensory reaction (for example, Fanger's olf panels),<sup>35</sup> respiratory irritation (for example, jar tests by sensitive individuals), skin and eye irritation, and a wide variety of health and comfort effects via exposure chamber studies.

### **RESEARCH NEEDS**

The current methods for evaluating indoor sources and sinks (and on the need to link source/sink emissions to human health and comfort) suggest several research needs:

1. The biological responses should be evaluated based on the true behavior of sources and sinks. The effects of variable concentrations over time and the effects of pollutant mixtures need to be determined. The short-term/high-concentration effects need to be differentiated from the long-term/low-concentration effects.
2. Biological response based tests that use animals and/or humans need to be developed for evaluating indoor sources. Objective measures of human health and comfort effects are needed, and should be correlated with pollutant levels.
3. Ultimately, human exposure studies should be conducted for a variety of indoor sources, and should use large test chambers and/or test houses. Multiple source/sink scenarios should also be examined.

### CONCLUSIONS

Much is known about the behavior of indoor sources and sinks, and methods are available, or are being developed, for determining the source/sink chemical emission rates. IAQ models can use these rates to predict indoor concentrations of the pollutants emitted. Unfortunately, the available information on human health and comfort is not consistent with the complex behavior of indoor sources (for example, multiple pollutants and emissions varying over time). Thus, methods are needed to directly link source/sink emissions to human health and comfort.

### SUMMARY

Indoor sources and their interaction with sinks play a major role in determining indoor air quality (IAQ). Methods for characterizing chemical emissions from material sources are discussed, including laboratory, dynamic chamber, and full-scale studies. Techniques for evaluating the behavior of indoor sinks are presented. Procedures for analyzing chamber test data to produce emission rates and adsorption/desorption rate constants are discussed, as is the use of these results in IAQ models to predict occupant exposure. Thoughts on how to link biological responses to source and sink emissions are presented, and source testing methods based on biological responses are briefly touched on. Finally, recommendations for future research are given.

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