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Source testing and data analysis for exposure and risk assessment of indoor pollutant sources

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Abstract

A major purpose of source testing is to provide information needed to determine the impact of sources on the indoor environment. Both the source testing data and the data analysis are important for meeting this need. Ideally the experiments would run long enough to capture all of the emissions from the source. Unfortunately, such testing is not practical for many types of sources such as pressed wood products and many building materials. Then the source emission models and consequent risk assessment must be based on incomplete knowledge of the total source emissions. The types of source data and source data analysis needed for development of source risk assessments are discussed in this paper. Suggestions for dealing with imperfectly characterized sources are made. The paper discusses only those aspects of the risk assessment related to the source and source emissions model. Aspects of risk assessment related to activity patterns and health effects of pollutants are not discussed.

Keywords: Source testing, risk assessment, exposure, IAQ modeling, source modeling

Introduction

Evaluation of the impact of indoor pollutant sources on indoor air quality (IAQ) and on the risk to building occupants requires an understanding of several factors including the source of the indoor pollutants, air exchange between the building and the outdoors, air movement within the building, interactions of the pollutant with surfaces within the building (i.e., sink effects), chemical or physical interactions affecting the pollutant concentration, individual activity patterns, and effects of the pollutants at various doses. A suggested process for carrying out these evaluations is shown in Figure 1, an extension of ideas presented by Tichenor et al. [1].

The success of source evaluation depends in great part on the data provided by source testing. These data must provide information necessary to develop a source model that predicts the emission rate as a function of time over the lifetime of the source. The source model must provide an adequate description of the peak emission rate, the long-term emission rate, and the total amount of pollutant emitted from the source.

The design of the source testing program must consider the needs of all steps in the process shown in Figure 1. For example, a source testing program that provides data necessary to predict the total emissions from a source is of little use if the main effects of the pollutant are due to peak exposure. On the other hand, a source test program that provides good information on the peak emissions but provides little information on the total emissions from the product is of little use if the effects of interest are due to total or time integrated exposure.

The purpose of this paper is to review the source evaluation process with emphasis on the types of information needed from source testing and source modeling. Examples using data from testing real sources will be used to illustrate important points. The emphasis of the paper is on source testing and source modeling; however, some discussion of general IAQ modeling, exposure modeling, pollutant effects, and risk analysis is provided to place the source testing and source modeling requirements in context.

Source Testing

"It is emphasized that small chamber evaluations are used to determine source emission rates. These rates are then used in appropriate IAQ models to predict indoor concentrations of the compounds emitted from the tested material. Consultation with IAQ modelers may be required to ensure that the small chamber test regime is consistent with the IAQ model assumptions. The concentrations observed in the chambers themselves should not be used as a substitute for concentrations expected in full-scale indoor environments." ASTM Standard guide for small scale environmental chamber determinations of organic emissions from indoor materials/products (D-5116-90).

As indicated by the quote from ASTM D-5116-90, the objective of source testing is to measure source characteristics that, with subsequent mathematical modeling, can be used

to predict the impact of the source. Source testing is not intended to be a small scale physical simulation of the indoor environment. However, source tests must be conducted to ensure that the source model developed from the tests can be scaled to deal with actual indoor environments.

Procedures for dynamic testing in small chambers are discussed by Tichenor [2] and in ASTM D-5116-90. These procedures provide a means of determining data for source model development using dynamic tests in environmental chambers. In these tests the pollutant source is placed in an environmental chamber. The chamber is then sealed, and a constant flow of clean air (air that has been filtered to remove particulate and gaseous contaminants) is passed through the chamber. The concentration of the pollutant leaving the chamber is measured at various times until the end of the test. Because the air in the chamber is assumed to be well mixed, the concentration leaving the chamber is the same as the concentration in the chamber. The data provide the time history of the pollutant concentration in the chamber. Procedures for obtaining an empirical source emission model from these data are discussed by Tichenor [2] and ASTM D-5116-90. Similar procedures can be used for large chambers.

Feigley et al. [3] discuss experimental methods for determining emission rates from coatings. Matthews et al. [4] and others have described methods for studying the emission of formaldehyde from wood products using large chambers. In these studies, the source is generally treated as a steady-state source; that is, the emission rate is assumed to be constant over the time period of interest.

Source testing of the long-term pollutant emissions from some sources, such as formaldehyde and volatile organic compounds (VOCs) from building materials, has been conducted by placing the materials in chambers for short periods of time, then calculating the emission rate based on the assumption that the source emission rate is constant over the time period, Mølhave et al. [5]. The materials are then placed in clean ventilated storage for a period of time, and the process repeated. This type of testing provides emission rates at various times. Because the emission rates of sources tested in this manner change very slowly with time, the assumptions involved in developing emission rates do not cause major errors.

Research is being conducted to develop source tests based on bioresponse instead of chemistry [6] and [7]. In bioresponse testing a biological system is exposed to the pollutant emissions. The response of the biological system is monitored over the emission history of the source. This response is then used to develop a model to estimate the health effects of the pollutants emitted from the source in actual indoor environments. The process shown in Figure 1 can be applied to the results from bioresponse tests, if bioresponse tests are to be used for risk assessment.

Source models

The concentration-versus-time data from source testing must be processed and analyzed to develop a source emission model. The general data analysis process is described by Dunn and Tichenor [8]. If the source has a constant emission rate, the emission rate, R (mass/time per unit source size), can be calculated from

$$R = C(N/L) \tag{1}$$

where C is the steady state chamber concentration (mass/volume), N (air changes/time) is the chamber air exchange rate, and L (chamber volume/source size) is the chamber loading.

For those sources that have emission rates that decrease over time, for example wood stain and other wet sources, the emission rate model is more complicated. For many sources, a first-order decay model of the form

$$R(t) = R_0 e^{-kt} \tag{2}$$

where R(t) is the emission rate at any time, t, R_0 is the emission rate at time zero, and k is a first-order emission rate decay constant (1/time), provides a good description of the emission rate as a function of time. The total emittable mass is R_0/k.

Other sources can be described by second- or third-order decay models of the form

$$R(t) = R_0 e^{-kt} + R_1 e^{-bt} + R_2 e^{-ct} \tag{3}$$

where R_1, and R_2 , b and c are empirical constants. The constants for these and other empirical models can be determined by a non-linear curve fit to the chamber concentration versus time data. Tools for carrying out the necessary calculations are readily available.

The constants developed for empirical models are often affected by test conditions. If the total emittable mass is increased, for example by heavy application of a wood stain, R_0 and/or k in the first-order decay model must change. If the mass transfer rate is limited by gas-phase mass transfer, the empirical constants are affected by the air speed over the source. Source testing should be conducted to provide scaling factors or under conditions similar to those encountered in indoor environments.

In order to overcome the scaling problem, source models based on mass transfer processes have also been developed. Tichenor et al. [9] proposed a mass transfer model for gas-phase-limited mass transfer. Other examples of source models based on fundamental processes include Christiansson et al. [10] who proposed a model for polyvinyl chloride (PVC) flooring. Various models for drying of paint (e. g., [11]) have also been proposed. The long-term emissions of formaldehyde from pressed wood and other products have

received considerable attention. The emission rates of these products are controlled by source-phase mass transfer processes (that is, the rate limiting step is controlled by processes occurring inside the pressed wood). Matthews et al. [4] presented a mass-transfer-based model for formaldehyde emissions from wallboard.

IAQ and exposure modeling

As is indicated by Figure 1, the source model is combined with building characteristics in an IAQ model to predict air concentrations inside the building. In general these predictions should provide a room-by-room prediction of the concentration-time history of the pollutant in the building. The predictions of the IAQ model are then used by an exposure model to predict individual exposure.

Individual exposure is determined by the time spent at a given pollutant concentration. Therefore, it is a function of both the building concentration time history and the individual activity pattern--that is, where the individual is located at what time. Building concentration can be predicted using mass-balance-based models such as EXPOSURE, [12]. Different activity patterns, for example, entering and leaving a building at different times or moving from one room to another, result in different exposures to the same building pollutant concentration time history. Sparks [13] discusses exposure modeling.

Two classes of exposure are of interest: instantaneous exposure, E_i,

$$E_i = C(t) \tag{4}$$

where C(t) is the concentration to which the individual is exposed at time t; and cumulative exposure, E_c, between times t_1 and t_2

$$E_c = \int_{t_1}^{t_2} C(t)dt \tag{5}$$

Which of these two classes of exposure is appropriate for a given situation depends on the nature of both the pollutant and the effect. The peak exposure is the maximum of the instantaneous exposure versus time curve. Calculation of exposure requires the value of the pollutant concentration to which an individual is exposed and the time exposed to that concentration. Both the value of the concentration and the time exposed to the concentration depend on the individual activity pattern.

As is indicated by Figure 1, risk modeling is the final step in the process of determining impact of sources on IAQ. Risk modeling integrates individual exposure, health effects, uptake, dose, and dose response to estimate the individual (or population) risk from the pollutant of interest [14]. Because source testing and source modeling provide key inputs to the risk analysis process, it is important to have a general idea of the types of effects and exposures of interest. In this way the source test and source model programs can be designed to provide the data necessary for risk analysis.

The effects of interest may be classified as: chronic, acute, and irritation/odor. The intensity and prevalence of these types of effects both depend to some extent on the maximum concentration to which each is occupant is exposed, the exposure duration, and its average concentration. Some effects may additionally have a delay between exposure and occurrence of effects. For these the entire time profile of exposure is needed. In general chronic effects are due to cumulative total exposure while irritation and odor responses occur at concentrations above some threshold level.

The IAQ, exposure, and risk analysis models must handle all the effects. The source testing requirements to provide the data necessary for these analyses are discussed below.

Source testing/source model requirements

Because source testing and the source model are closely related, the discussion of requirements will include both. The major requirements for the ideal source model are:

- It must describe the peak emission rate.
- It must describe the long-term emissions in terms of average emission and the time profile of the emission.
- It must account for all the emittable pollutant mass in the source.

Each of these requirements, and its impact on source testing, is discussed below.

Peak emission rate

Source testing must provide data to ensure that the source model adequately describes the peak emission rate. The type of data needed depends on the type of emission model. If the emission model is empirical, source testing must provide sufficient data in the first several hours to allow accurate curve fit to the data. Two to four data points per hour for the first 4 to 6 hours are often necessary. Data requirements for mass-transfer-based models are discussed in reference [9].

Failure to adequately describe the peak emission rate will make prediction of peak concentration and peak exposure impossible. The failure to adequately describe the peak emission rate will reduce the reliability of the predictions of threshold effects. In many scenarios the peak exposure is a major fraction of an individual's total cumulative exposure. Thus failure to accurately predict the peak, can result in large errors in prediction of total exposure. Finally, because the peak concentration often determines how much material is adsorbed by re-emitting sinks, a poor estimate of the peak emission rate can result in poor estimates of long-term exposure even for those individuals not exposed to the peak.

Because emissions from sources with high initial emission rates are likely to be controlled by gas-phase mass transfer, appropriate mass-transfer-based models can often be used to predict initial emission rates. An example, using data from [9], is shown in Figure 2. The data in Figure 2 are from an IAQ test house, and the model predictions are based on the

IAQ model EXPOSURE [12]. Note that the mass transfer model provides a much better description of the peak concentration than does the first-order decay model.

Long-term emissions

The source model must be able to account for all the mass emitted from the source. This is the mass that determines the prevalence of effects such as cancer due to long-term exposure to the emissions from the source. This requirement may be difficult to meet for many sources. For example, formaldehyde emissions from many products have an emission half life (i.e., the time required for the emission rate to decay to one half of its initial value) of several years. Some sources appear to have a three-phase emission: a fast emission with a half life of less than a day, a slow emission with a half life of about a year or so, and a very slow emission with a half life of several years. An example of such a source is shown in Figure 3. The source in Figure 3, a collection of furniture, is described in [15]. This figure also demonstrates the problems encountered in developing models for sources with long-term emissions. Mølhave et al. [15] believe that the three-phase model is the best model for this source. However, without additional data, it is difficult to choose between the two-phase model and the three-phase model. The three-phase model was selected because it was believed to provide a better estimate of the very long-term (up to 70 years) emissions.

If the emissions from a source such as that shown in Figure 3 are to be modeled using an empirical model, the source testing must be conducted for a long time. In many cases it is impractical to run the emission tests long enough to define the long-term emissions. If the total emittable mass is known, an empirical model that accounts for all the emittable mass can be developed from short-term testing. The total emittable mass can also be used to develop a conservative estimate of the long-term risk.

Unfortunately, the total amount of emittable material is often not known. In this case the long-term risk can be calculated by dividing the source emissions into two phases. Phase 1 covers the time covered by the source tests and uses the model developed from the source test data. Phase 2 covers the time after the end of the source tests. Source emissions in phase 2 are assumed to be constant at the emission rate predicted by the model at the time the tests ended. This two-phase approach is likely to provide a conservative estimate of the long-term risk.

A second method for dealing with the case of unknown total emittable mass is to begin with the two-phase approach described above. If the estimated long-term risk is acceptable, testing can stop. If the long-term risk is not acceptable, source testing is continued for an additional time. The two-phase risk analysis is then repeated. If the risk is acceptable, then testing can stop.

A third method for dealing with the case of unknown total emittable mass is to develop the source emission model using the source test data. Then run the source test for an additional period of time. If the model predicts this last emission rate accurately (the

required accuracy should be defined before the experiment is run), the long-term risk can be analyzed using the resulting emission model.

Total emittable mass

Source testing should be designed to provide an independent estimate of the total amount of pollutant that can be emitted (the total emittable mass). An independent estimate of total emittable mass provides an excellent quality assurance check to the emission model. A simple mass balance can be calculated to determine if the emission model is adequate. If dynamic chamber tests are being used, the mass balance of the mass emitted during testing and that of the total emittable mass should be compared as a quality control step. Note that the total emittable mass of pollutant is not always the same as the total amount of pollutant present. For example, some of the pollutant can be bound to the source and thus never emitted. Test methods must be designed to separate the emittable and non-emittable pollutant masses.

As discussed above, total emittable mass is necessary to estimate the long-term cumulative exposure. Also mass-transfer-based models often require the total emittable mass as a model parameter [9]. Total emittable mass can often be quantified by direct analysis of the source (e.g., using ASTM methods described by Brezinski [16]). Good methods for estimating total emittable mass do not exist for some sources, such as formaldehyde emissions from particle board. The reasons for the lack of good methods for determining the total emittable mass vary depending on the source. In the case of formaldehyde emissions from particle board, test methods to determine total formaldehyde can release formaldehyde that is bound to the board. Additional research to develop methods for estimating total emittable mass from these sources would be useful.

Other considerations

Although source tests are not intended to simulate real building conditions, the tests should be conducted under conditions that allow easy scaling of the test results to building conditions. The requirements of the source emission model will determine how best to achieve easy scaling. If dynamic chambers are used, the emission regime should be consistent with typical indoor environments. For example, dynamic chamber tests of sources governed by gas-phase mass transfer should be conducted at air speeds of 0.05 to 0.1 m/s near the surface of the source. (These air speeds are typical of those found in indoor environments.) A small fan can be used to achieve such conditions. Velocity can be measured with hot wire or film anemometers.

The results of source tests should be reported in terms of a source emission model. The data reduction used to develop the emission rate model should be consistent with the source behavior and the type of source model. A common error in analyzing source test data is to calculate daily emission rates for time dependent sources by assuming that the emissions are constant for each day. The source emission model produced by such an

analysis is incorrect. The methods discussed in [2] and ASTM D-5116-90 must be used to develop the emission model.

Conclusions

Source testing is intended to provide data needed to evaluate the impact of the source on the indoor environment. This evaluation is accomplished, not by trying to physically simulate the indoor environment in the chambers, but by mathematical modeling. The source tests provide data needed to build mathematical models of the source emissions. The models must account for the time history of the emissions and accurately predict the peak emission rate as well as the long-term emission rate. The model should also predict the total emissions from the source. The design of the source test program depends on the needs of the source model and the nature of the effects, exposures, and risks being modeled.

Where significant source emissions occur for several years, source testing to define the long-term emissions is difficult. The best way to deal with this situation is to obtain an independent estimate of the total emittable mass. A risk assessment can then be conducted using the available test data and the total emittable mass. If an estimate of the total emittable mass is not possible, one of the methods below could be applied:

1. Conduct the risk analysis based on the source emission model developed from the data and the assumption that the source emission rate for all times after the last measurement is constant with a value equal to that calculated for the last measurement time.
2. Conduct the risk analysis as above and if the estimated risk is acceptable stop testing. If the risk is not acceptable, continue testing and repeat the risk analysis using the new data.
3. Use the data to develop a source emission model. Continue testing for at least 25 percent of the testing time, and use the model to calculate the emission rate for the new tests. If the model prediction is accurate, use the model for the risk analysis.

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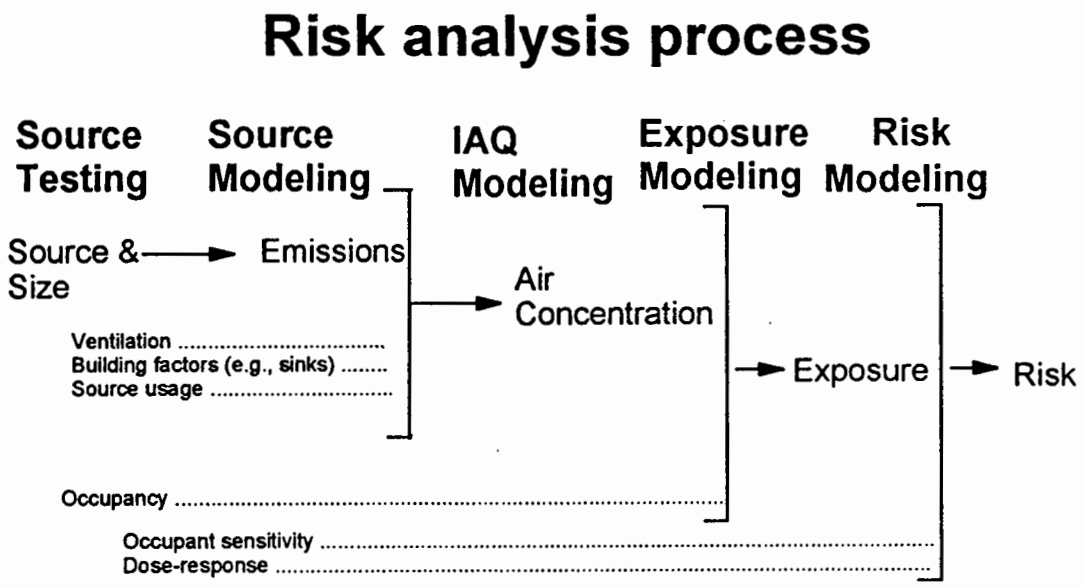

Figure 1. Principles of assessing risk due to indoor sources.

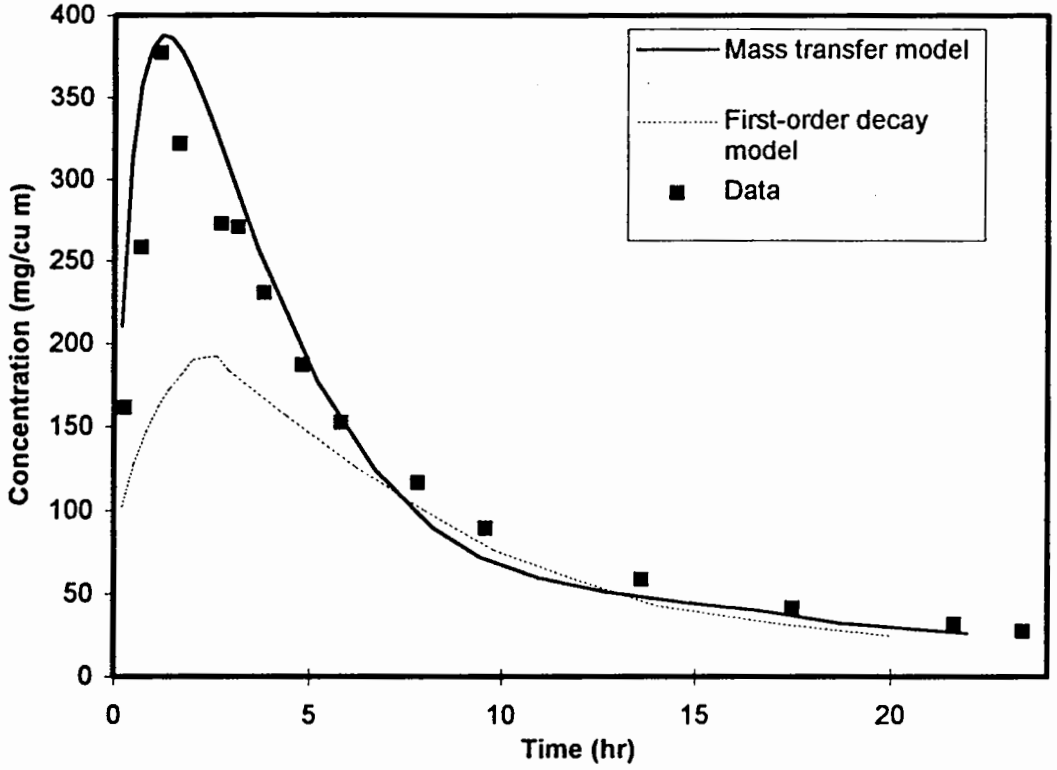

Figure 2. Use of mass-transfer-based model to improve prediction of the initial concentrations.

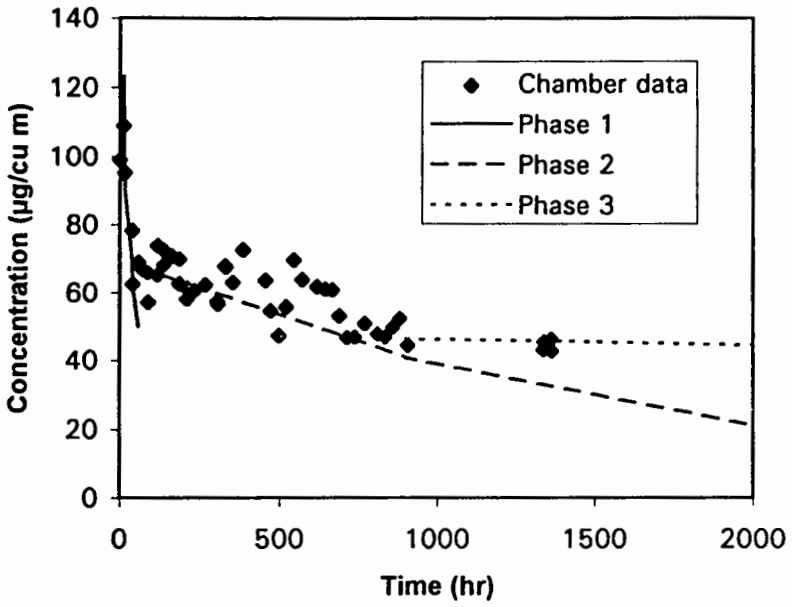

Figure 3. Formaldehyde emissions showing three-phase emissions [15].

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Mathematical Models	Stationary Sources	12A
Exposure	Indoor Air	06S
Data Processing	Source Testing	09B
	Risk Assessment	
	Source Modeling	

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