#4479

A Computer Model for Calculating Individual Exposure Due to Indoor Air Pollution Sources

L. E. Sparks and W. G. Tucker
U. S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Indoor Air Branch
Research Triangle Park, NC 27711

A model for calculating individual exposure to indoor air pollutants from sources is presented. The model is designed to calculate exposure due to individual, as opposed to population, activity patterns and source use. The model uses data on source emissions, room-to-room air flows, air exchange with the outdoors, and indoor sinks to predict concentration-time profiles for all rooms. The concentration-time profiles are then combined with individual activity patterns to estimate exposure. The agreement between predicted concentration-time profiles and experimental data is excellent.

Introduction

An indoor air quality (IAQ) computer model, INDOOR, was developed to use emission characteristics of sources to predict in-room pollutant concentrations (1). INDOOR's predictions for several sources have been verified by experiments conducted in an IAQ test house (2, 3), and emission characteristics have been determined using techniques in Tichenor (4).

INDOOR, however, does not allow calculation of individual exposure due to a given source and personal activity pattern. The ability to estimate individual exposure is necessary before guidance on exposure reduction can be given. Therefore, a new model, EXPOSURE, that allows analysis of exposure due to indoor sources (given pollutant source characteristics and individual activity patterns) was developed.

General mathematical framework of the model

EXPOSURE is a multiroom model based on INDOOR. EXPOSURE allows calculation of pollutant concentrations based on source emission rates, room-to-room air movement, air exchange with the outdoors, and indoor sink behavior.

Each room is considered to be well mixed. The validity of the well mixed assumption was verified in several experiments in the EPA IAQ test house (1) and by data reported by Maldonado (5).

A mass balance for each room gives:

$$V_i \frac{dC_i}{dt} = C_{iIN}Q_{iIN} - C_{iOUT}Q_{iOUT} + S_i - R_i \qquad (1)$$

where V_i is the volume of the room, C_{iIN} is the concentration entering the room, Q_{iIN} is the air flow into the room, C_{iOUT} is the concentration leaving the room, Q_{iOUT} is the air flow leaving the room, S_i is the source term, and R_i is the removal term. The removal term, R_i, includes pollutant removal by air cleaners and sinks.

The well mixed assumption requires that C_{iOUT} equals C_i. Equation (1) can be rewritten as:

$$V_i \frac{C_i}{dt} = C_{iIN} Q_{iIN} - C_i Q_{iOUT} + S_i - R_i \qquad (2)$$

where the subscript i refers to room i for a room in a set of multiple rooms. Equation (2) is one of a set of identical equations that must be solved simultaneously in a multiple room model.

EXPOSURE uses a fast discrete time step algorithm developed by Yamamato et al. (6) to solve the series of equations. The algorithm is based on the assumption that for sufficiently small time steps, dt, the source and sink terms and all neighboring concentrations are constant. The exact solution to equation (2) can then be used to calculate the concentration at the end of the time step. The exact solution is:

$$C_i = C_i(t_0)e^{-L_i t} + \frac{P_i}{L_i}[1 - e^{-L_i t}] \qquad (3)$$

where $C(t_o)$ is the concentration at time t_o, t is some time greater than t_o, L_i is Q_{iOUT}/V_i, and P_i is given by:

$$P_i = \frac{1}{V_i}[\sum_{j=1, j \neq i}^{n} Q_{ij} C_j(t) + S_i - R_i + Q_{ia} C_a] \qquad (4)$$

where Q_{ij} is the air flow from room j into room i, $C_j(t)$ is the concentration in room j at time t, Q_{ia} is the air flow to the outdoors, and C_a is the outdoor concentration. Equation (3) is stable for all time steps and is accurate for sufficiently small time steps. (The size of the time step depends on how rapidly concentrations are changing. In general a time step of 1 minute is small enough for situations when concentrations are changing rapidly, and time steps of several minutes are adequate when concentrations are near steady state. The model automatically adjusts the time step to maintain a balance between speed and accuracy.)

Source terms

The model incorporates a wide range of emission characteristics to allow simulation of the range of sources encountered in indoor spaces. Several sources are allowed in each room.

The model includes a data base of source emission rates for these various sources based on research conducted by the Indoor Air Branch, Air and Energy Engineering Research Laboratory, of EPA. The user can add to the data base and can override the data base emission rates.

Sink Terms

Research in the EPA test house and small chamber laboratory has shown that sinks (i.e., surfaces that act to remove pollutants from the indoor air) play a major role in determining indoor pollutant concentrations. These sinks may be reversible or irreversible. A reversible sink re-emits the material collected in it, and an irreversible sink does not. Sink behavior depends on the pollutant and the nature of the sink. Considerable research is necessary to define the behavior of sinks.

The sink model used in EXPOSURE is:

$$R_s = k_a C A_{sink} - k_d M_s^n A_{sink} \tag{5}$$

where R_s is the rate to the sink (mass per unit time), k_a is the sink rate constant (length per time), C is the in-room pollutant concentration (mass per length cubed), k_d is the re-emission or desorption rate constant, M_s is the mass collected in the sink per unit area (mass per length squared), n is some power between 1 and 2, and A_{sink} is the area of the sink (length squared). For typical gaseous organic pollutants of interest in indoor air: k_a ranges from about 0.1 to 0.5 m/h; the sink re-emission rate, k_d, ranges from about 0.003 to 0.009; and n ranges from 1 to 1.5. Experiments are under way to provide estimates of k_a and k_d for a range of pollutants and sink materials.

Sinks reduce the peak exposure to pollutants slightly but increase the cumulative exposure because of re-emissions.

Exposure

Because the most common route for exposure to indoor air pollutants is via inhalation, it is convenient to define inhalation exposure, E_i as:

$$E_i = C(t)bv \tag{6}$$

where C is the pollutant concentration, b is the breathing rate, and v is the volume per breath. The exposure defined by equation (6) is instantaneous; i.e., the exposure at any instant in time, t. The peak exposure is the maximum of the instantaneous exposure versus time curve. The cumulative inhalation exposure, E_{ic}, is given by:

$$E_{ic} = \int_{t1}^{t2} C(t)bv\,dt \tag{7}$$

The advantage of defining inhalation exposure is that the exposures calculated by the computer can be used without requiring the user to manually calculate the amount breathed.

For exposure by mechanisms other than inhalation, the instantaneous exposure, E, to a pollutant at time t is the concentration, C(t), the person is exposed at time t:

$$E_c = \int_{t1}^{t2} C(t)dt \qquad (8)$$

The cumulative exposure from t1 to t2 is given by:

$$E = C(t) \qquad (9)$$

Calculation of exposure requires the pollutant concentration, the time exposed to the concentration,and (for inhalation exposure) the breathing rate and the volume per breath. The time exposed to the concentration depends on the individual activity pattern.

An activity pattern, in the context of the model, is defined by providing the time a person enters and leaves the various rooms of the building, or leaves the building for the outdoors. The model allows up to 10 room changes per day. The model is based on a 24-hour day. The activity patterns (and most source usage patterns) in the model repeat from day to day.

The model provides instantaneous exposure time plots and cumulative exposure time plots for individual activity patterns. The instantaneous exposure allows identification of high exposure situations and of the peak exposure.

While the model was designed to allow assessment of impact of indoor air pollution sources and sinks and IAQ control options on individual exposure from specific activities, it can also be used to help estimate population exposures if data on population activity patterns are available. Model runs can be made for each activity pattern and then the results can be weighted according to the population statistics.

Model verification

The model predictions of concentration versus time have been compared to experimental data from the EPA IAQ test house. In all cases the agreement between predictions and experiment has been excellent. An example from a recent experiment is shown in Figure 1.

Exposure predictions

The examples in this section demonstrate some of the model's capabilities. The first example is calculation of the exposure to an aerosol spray product. The activity patterns are for a person who uses the product in a bathroom for 10 minutes moves to the living room and then leaves the building after 1 hour; and for a person who does not enter the bathroom but stays in the building for 24 hours. The instantaneous and cumulative inhalation exposures for the two individuals are given in Figures 2 and 3. Note that, while the initial instantaneous exposure for the person using the product is much higher than for the other person, the cumulative exposure for the person using the product is less. However, the exposure for the person using the product is probably underestimated in this example. The local concentration near the person is somewhat higher for several minutes than the average room concentration. EXPOSURE can deal with this situation if a pseudo room with a volume of about 5 m^3 and an air exchange of 30 m^3/h with the rest of the room is defined. For the case shown in Figure 2, the difference in exposures is not great because the volume of the bathroom is relatively small (20 m^3).

The second example shows the exposure due to wood stain, a "typical wet source." Because of adsorption and re-emission from sinks, the exposure lasts for a considerable time. The cumulative exposures for a person spending 24 hours in the building and for a person spending 16 hours in the building (starting 8 hours after the stain is applied) are shown in Figure 4 both with and without a sink. Note the major effect of the sink on the exposure of the person spending part time in the building.

The two examples model experiments conducted in the EPA test house. All model input is based on the conditions in the test house at the time of the experiments. The model predictions of concentration versus time for both cases are in excellent agreement with the test house data.

Conclusions

EXPOSURE provides a tool to estimate individual exposure to air pollution from a wide range of indoor sources. The model allows analysis of a wide range of activity scenarios in a single model calculation. The effect of mitigation options on individual exposure can be evaluated by simulating the mitigation option in the model.

The documentation for EXPOSURE is being written. The documentation and MS-DOS readable disk will be available from NTIS as soon as they have been cleared for publication by EPA.

References

1. Sparks, L. E. (1988) Indoor Air Quality Model Version 1.0, EPA Report EPA-600/8-88-097a, (NTIS PB89-133607),Research Triangle Park, NC.

2. Sparks, L. E., M. D. Jackson, and B. A. Tichenor (1988) Comparison of EPA test house data with predictions of an indoor air quality model, Proc. IAQ 88 Atlanta, GA.

3. Sparks, L. E., B. A. Tichenor, M. D. Jackson, and J. B. White (1989) Verification and Uses of the Environmental Protection Agency (EPA) Indoor Air Quality Model, Proc. IAQ 89, San Diego, CA.

4. Tichenor, B. A. (1989) Indoor Air Sources: Using Small Environmental Test Chambers to Characterize Organic Emissions from Indoor Materials and Products, EPA Report EPA-600/8-89-074, (NTIS PB90-110131), Research Triangle Park, NC.

5. Maldonado, E. A. B. (1982) "A method to characterize air exchange in residences for evaluation of indoor air quality," Ph.D. Dissertation in Mechanical Engineering, Iowa State University, Ames, IA.

6. Yamamoto, T., D. S. Ensor, P. A. Lawless, A. S. Damle, M. K. Owen, and L. E. Sparks (1988) Fast Direct Solution Method for Multizone Indoor Model, Proc. Indoor Air Modeling, Champaign, IL.

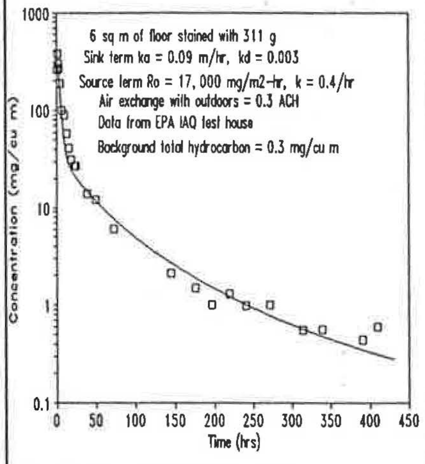

Figure 1. Total hydrocarbon concentration in living room from wood stain.

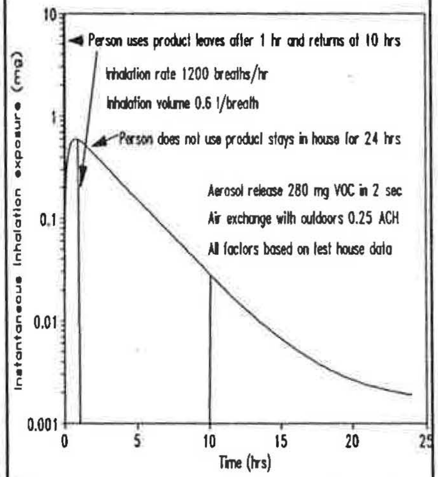

Figure 2. Instantaneous inhalation exposure to VOC from aerosol spray product

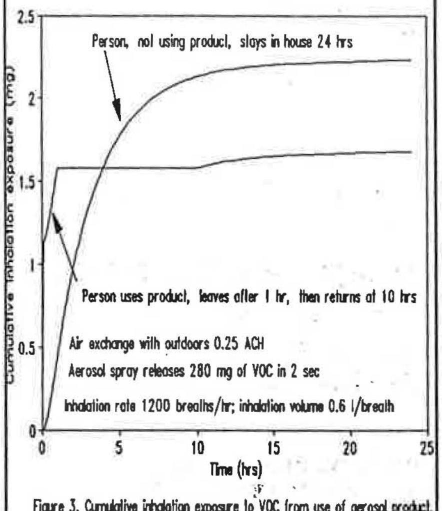

Figure 3. Cumulative inhalation exposure to VOC from use of aerosol product.

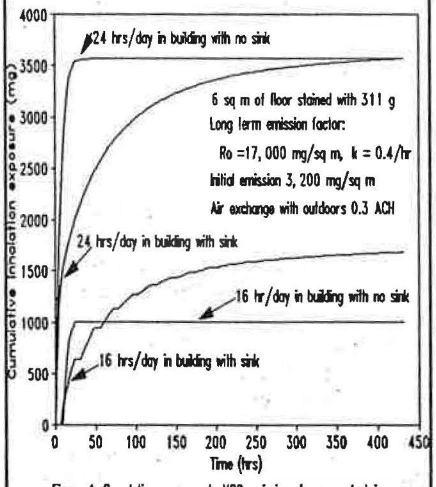

Figure 4. Cumulative exposure to VOC emissions from wood stain.