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VERIFICATION AND USES OF THE ENVIRONMENTAL PROTECTION AGENCY (EPA) INDOOR AIR QUALITY MODEL

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ABSTRACT

This paper describes a set of experiments used to verify an indoor air quality (IAQ) model for estimating the impact of various sources on indoor air quality in a multi-room building. The model treats each room as a well-mixed chamber that contains pollutant sources and sinks. The model allows analysis of the impact of room-to-room airflows, HVAC (heating, ventilating, and air-conditioning) systems, and air cleaners on IAQ. The model is written for personal computers.

The experiments were conducted in a test house. Three different pollution sources were used in the experiments—moth crystals, kerosene heaters, and dry-cleaned cloths. The model predictions were in good agreement with the experimental data, especially when a sink term was included in the model.

The paper presents a brief discussion of the theory on which the model is based. Preliminary data and theory of sources and sinks are also discussed. Examples demonstrating the use of the model to analyze IAQ control options and to estimate exposure from a pollutant are included.

INTRODUCTION

Indoor air quality (IAQ) is determined by the interactions of sources, sinks, and air movement between rooms and between the building and the outdoors. Sources may be located in rooms, in the HVAC system, or outside the building. Sinks (i.e., materials that adsorb indoor pollutants) may be located in the same locations. Sinks may also act as sources when the pollutant concentrations drop below a given value.

Air movement in a building consists of:

1. Natural air movement between rooms.
2. Air movement driven by a forced-air (HVAC) system.
3. Air movement between the building and the outdoors.

A model to describe indoor air pollution must include all three types of air movement. The model must also be able to describe the behavior of sources which may be time dependent. Finally, the model must be able to include the effects of sinks. This paper describes a personal-computer-based model, INDOOR, that includes all these factors.

OTHER INDOOR AIR MODELS

Indoor air quality models can be divided into two basic classes—micro models and macro models. The micro models are designed to analyze the details of the airflow in a building and solve the Navier-Stokes equations. Macro models are designed to analyze the bulk room-to-room flow of air and pollutants and solve the differential equations derived from overall mass balances. INDOOR is a macro model designed to run on a personal computer.

TABLE 1

Representative List of Indoor Air Quality Models

Author	Reference	Comments
Axley and Grote	1	PC Based Multizone.
Ryan et al.	2	Airliner cabin 4 zones.
Rodgers	3	2 zones.
Ishizu & Kaneki	4	Multizone.
		Traynor
	5	Single zone long term.

Model references:

1. General Indoor Air Pollution Concentration Model (Phase II Report), J. Axley and R. Grote, Washington, DC: U.S. Department of Commerce, National Bureau of Standards (1986).
2. P.B. Ryan, J.D. Spengler, and P.F. Halfpenny, *Atmos. Envir. 22* (6), 1031 (1988).
3. L. Rodgers, *ASHRAE Trans. 86* (Part 2), 92 (1980).
4. Y. Ishizu and K. Kaneki, *Trans. SHASE No. 24*, 24 (1984).
5. G. Traynor, Presentation at Symposium on Indoor Pollutant Sources and Sinks, Gaithersbury, MD (1989).

INDOOR is one of several macro models for describing indoor air quality. Many of these models are not generally available and were developed for specific purposes. A representative list of other macro models is given in Table 1.

The features that set INDOOR apart from most of the models listed in Table 1 are:

1. Ease of use.
2. Incorporation of source and sink terms.
3. Incorporation of air cleaners.
4. Incorporation of strong ties between source studies and test house studies.

THEORY

The full description of the model is given by Sparks (1988) so only a brief overview will be given here.

The pollutant concentration in a room is calculated by a mass balance of the various pollutant flows. For the single room shown in Figure 1:

Amount in − Amount out + Amount produced − Amount removed = Amount accumulated

The analysis can be extended to multiple rooms by writing a mass balance equation for each room and the building as a whole. The result is a system of equations. One constraint on the equations is that the mass of air entering a room must equal the mass of air leaving a room. Another constraint is that the mass of pollutant must be conserved for the building as a whole.

The type of mixing between the pollutant and the room air must be specified before the mass balance equations can

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be used in a model. Because mixing is complex, the exact mixing cannot be specified; simplifying assumptions must be made. Plug-flow and well-mixed are two common mixing possibilities.

In the plug-flow mixing model, the pollutant concentration varies from point to point along the airflow path. In the well-mixed model, the pollutant concentration is the same for every point in the room. Experimental data from test houses show that pollutant concentration does not vary significantly from point to point in a room—especially on a time scale of several minutes, which is the time scale of interest for the computer model. Therefore, the well-mixed assumption was used in the IAQ model.

Once the mixing is defined, the various mass balance equations discussed above can be used to write a set of differential equations. The equation for a single room is:

$$VdC/dt = C_oQ_{in} + P - S - CQ_{out}$$

where V is the volume of the room, C is the room concentration at time t, C_o is the concentration outside the room, Q_{in} is the flow entering the room, P is the mass produced, S is the mass lost to the sink, and Q_{out} is the airflow leaving the room. For multiple rooms, the single equation is replaced by a system of equations.

The equations for the IAQ model can be solved numerically by a number of standard techniques. A modified midpoint method described by Press et al. (1987) is used in the model. This method is faster than fourth-order Runge Kutta for the same accuracy. The modified midpoint method is stable for reasonable values of the step size used in the calculations. The program monitors the behavior of the solution and, if instability is detected, a warning message is printed. The user must reset the step size and restart the calculations.

SOURCE TERMS

The source term is the most important factor in determining the concentration of pollutant. The source term is defined as the amount of material emitted by the source per unit time. The source term is calculated by multiplying the source size by the source emission rate. The source emission rate is the amount of material released by a unit source per unit time. The current version of the model uses empirical factors for the emission rates from the sources. The emission rates for most of the sources in the model are based on chamber studies conducted by the Environmental Protection Agency. As additional data are acquired from these chamber studies, they will be added to the data base supporting the model.

Sources can be divided into several classifications based on the time dependency of the emission rate. The classifications used in the model are:

1. Random short-term on/off sources (e.g., cigarettes).
2. Long-term on/off sources (e.g., heaters).
3. Long-term steady-state sources (e.g., moth crystals).
4. Sources with high initial emission rates that decay with time (e.g., floor wax).

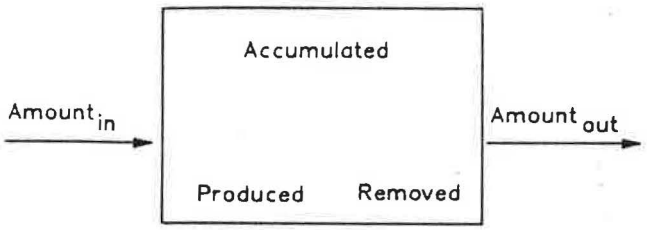

Figure 1 Single-room airflows

The model accommodates all these possibilities in an idealized fashion.

Although the empirical emission factors appear to work well in the model, emission rates based on an understanding of the pollution sources would be more generally useful. Theoretical emission rates would allow analysis of sources that have not been studied in chambers, for example. Limited work is under way to develop such models. These models are based on analysis of the mass transfer processes that occur at the source. Preliminary results of modeling of moth crystals and solvents provide predictions that are in good agreement with experimental data.

Sinks

Sinks are surfaces and materials that remove pollutants from the indoor air. The material collected by the sink may remain in the sink or be reemitted later. Although the importance of sinks in determining indoor air quality is generally recognized, there are few data on the behavior of sinks.

A simple model of sink behavior is used in the IAQ model. The rate of material to the sink, R_{sink}, is assumed to be:

$$R_{sink} = k_{sink}\, C\, A_{sink}$$

where k_{sink} is the rate to the sink (units length/time), C is the pollutant concentration in the room, and A_{sink} is the area of the sink. This equation can be rewritten as

$$R_{sink} = ueCA_{sink}$$

where u is the deposition velocity and e is the efficiency of the sink. If $e = 1$, all the pollutant that hits the sink sticks and if $e = 0$ none of the material that hits the sink sticks. The deposition velocity can be estimated from the diffusivity of the pollutant (Sparks 1988). For many volatile organic compounds (VOC) the deposition velocity is in the range of 0.2 to 0.3 m/h. For particles the deposition velocity is about 0.05 m/h.

Sinks can reemit some or all of the material collected in them. The emissions from the sink can be estimated by:

$$E_{sink} = k_eM_{sink}A_{sink}$$

where E_{sink} is the emission rate from the sink, k_e is an emission rate constant for the sink, and M_{sink} is the mass collected in the sink. Research is under way to determine k_e and to better understand sink emissions.

AIRFLOWS

The airflow in a building consists of forced airflows due to the HVAC system and natural airflows due to normal temperature and pressure differences within a building. These airflows determine how pollutants are dispersed in a building. When the airflows are dominated by HVAC flows, the HVAC flows can be measured and used in the model. If measurements are not available, design HVAC airflows, or airflows calculated based on ASHRAE guidelines, can be used. If all else fails, a rule of thumb that an HVAC provides about 5 to 7 air changes per hour (ach) can be used. Note that only a fraction of the HVAC airflow is fresh outside air; the bulk of the HVAC airflow is recirculated air.

When airflows are not dominated by the HVAC system,

estimates of the room-to-room airflows are needed. There are few data available on these flows. Data based on limited measurements indicate that if doors between rooms on the same floor of a building are open, the room-to-room airflows for these rooms are several air changes per hour. Data with doors closed and for airflows between floors are not generally available. Airflows between floors in a multi-story building are generally much less then the room-to-room airflows. Analysis of very limited data indicates that floor-to-floor airflows in a residence might be 30 to 40 m^3/h and in a larger building might be up to 90 m^3/h.

Note that although the room-to-room airflows are important, they do not have to be known with high precision. For example, calculations show that for the case of a strong source in a small room, a factor of 10 change in airflow between the room with the source and an adjoining room changes the concentration in the room with the source by about a factor of 2 and the concentration in the other rooms by less than 50%.

MODEL VERIFICATION

Experiments to verify the model were conducted in a test house (see Figure 2 for a floor plan). The pollutant sources for the experiments were moth crystals, dry cleaning, and kerosene heaters. In all three cases the pollutant emission rate was determined from chamber experiments. House characterization and each of the experiments are discussed briefly below.

House Characterization

Experiments were conducted to estimate the overall air exchange between the house and the outdoors, the room-to-room airflows, and the HVAC airflows. Some of these experiments were qualitative in nature and were designed to test the reasonableness of the values used in the model.

Air exchange with the outdoors was determined by blower door tests and SF_6 tracer studies. The agreement between the two methods was quite good. The overall air exchange between the outdoors and the test house was 0.35 h^{-1} for most of the conditions encountered in the experiments discussed below. The air exchange rate was 0.4 h^{-1} for the kerosene heater tests. The increase in air exchange rate for the kerosene heater test was caused by opening a window 5 cm. SF_6 measurements were commonly made for all experiments to ensure that the default value had not changed.

The HVAC airflows were determined by measuring the HVAC airflow into each room and the overall return air. The two airflows balanced within 10%. Because many of the experiments were conducted with the HVAC fan on, the HVAC airflows provided the dominant airflow pattern for the house. This pattern was HVAC flow into each room and flow from each room into the hall and then to the HVAC return. The HVAC provided about 6 air changes per hour for each room.

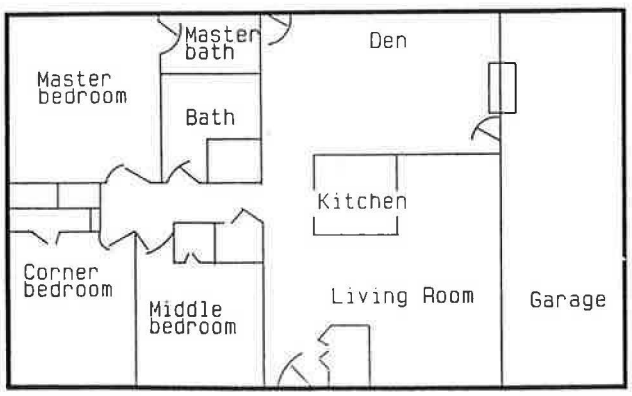

Figure 2 Test house diagram

TABLE 2

Comparison of Measured and Predicted p-dichlorobenzene Concentrations.

Room	Measured ug/m^3	Predicted ug/m^3
Closet	74	74
Corner bedroom	5.1	5.7
Master bedroom	3.8	4.0
Den	3.7	4.0

Although the HVAC airflow provided the dominant airflow pattern for the test house, there were secondary airflows between rooms that contributed to pollutant transport. These airflows were qualitatively estimated using neutral density soap bubbles. The bubbles followed the airflow in a room and between rooms. The bubbles showed that, even with the HVAC fan on, there was significant airflow directly between rooms with no mixing in the hall and between rooms and the hall with mixing in the hall.

Airflows between the closet in the corner bedroom and the bedroom were observed with the bubbles and were measured with a hot wire anemometer. These airflows were important for the moth crystal and dry-cleaning studies because the pollutant source was located in the closet.

Additional experiments to further characterize the airflows in the test house are planned.

Whenever possible, airflows should be determined by direct observation instead of via tracer gas measurements. The use of tracer gas measurements introduces circular logic into the model verification process. When tracer gas measurements are made, a model similar to the model being verified is used to estimate the airflows from the tracer concentration measurements. Then these airflows are used in a model to estimate pollutant concentrations. Even though the models are not identical, the basic assumptions used in the various models are essentially the same.

Additional house characterization tests were conducted and are reported by Jackson et al. (1987).

Moth Crystal Experiments

For the moth crystal experiments, the moth crystal cakes were placed in the closet of the corner bedroom (Clayton et al. 1988). The closet door was closed and the fan for the air-conditioning system was run continuously. The source term for use in the model was determined in small chamber studies (Nelms et al. 1987). The sink rate term was 0.3 $m/h/m^2$. The sink did not reemit. Measurements of p-dichlorobenzene concentration were made in the closet, the corner bedroom, the master bedroom, and the den. SF_6 measurements showed that the air exchange with the outdoors was 0.35 ach. The sink strength was estimated as discussed in the section on sinks. The results of the comparison between model predictions and experimental data are shown in Table 2. The agreement is very good.

As noted above, the model runs were made for a non-emitting sink. Measurements of the p-dichlorobenzene concentration in the test house after the moth crystals were removed from the closet showed that the sink did emit. Estimates of the sink emission term showed that the emission

TABLE 3

Comparison of Measured and Predicted Particulate Concentration from Kerosene Heaters.

Heater	Location	Predicted ug/m³	Measured ug/m
Convective	Den	60	68
Radiant	Master bedroom	52	36
Radiant	Den	285	279
Radiant	Master bedroom	235	242

rate from the sink was much less than the sink collection rate as long as the moth crystal source was in the house. However, the sink emission rate was high enough to maintain p-dichlorobenzene concentrations near 1 mg/m³ for several days after the moth crystals were removed.

Kerosene Heater Experiments

For the kerosene heater experiments, the heater was placed in the den. The heater was operated with a window open 5 cm. The particulate emission factors for use in the model were determined from large chamber studies. Particulate measurements were made in the den, the master bedroom, and the corner bedroom. SF_6 measurements showed that the air exchange with the outside was 0.4 ach. The sink strength was based on deposition velocities for small particles calculated from Fuchs (1964). The comparison between measurements and experiments is shown in Table 3. The experimental data for the kerosene heater experiments are reported in Jackson et al. (1988).

Dry Cleaning

For the dry-cleaning experiments, a standard load of dry cleaning was placed in the closet of the corner bedroom. The HVAC was allowed to operate normally (i.e., in an on/off cycle determined by the need for air conditioning). The source term for the dry-cleaning experiment was determined from small chamber experiments. The source term is plotted in Figure 3. A preliminary experiment was conducted to provide an estimate of the sink effect for the perchloroethylene. The sink experiment indicated that the sink was re-emitting.

Because the source term was not steady and the sink was re-emitting, the dry-cleaning experiment provided a more complicated test of the model than did the moth crystal and kerosene heater tests. The results of the comparison between the model and experimental data are shown in Figure 4 (taken from Tichenor et al. 1988).

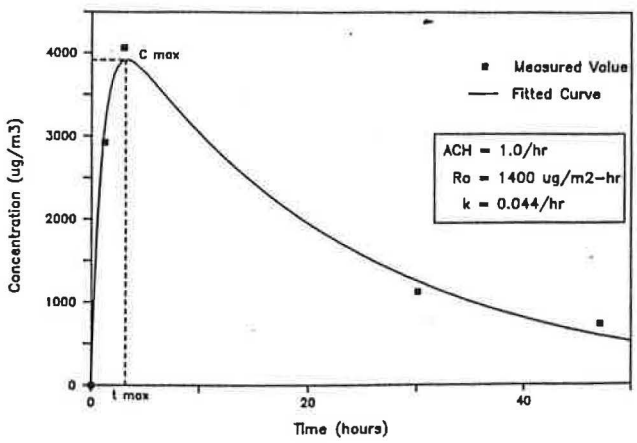

Figure 3 Perchlorethylene emissions from dry cleaning (modeling of small chamber data)

TABLE 4

Analysis of IAQ Control Options

Option	Pollutant Concentration, µg/m³ Room 1	Other rooms
Baseline	4166	1666
60% outside air in HVAC	3333	833
100% outside air in HVAC	3000	500
50% efficient air cleaner	3000	500
70% efficient air cleaner	2650	150
100% efficient air cleaner	2500	0
200 m³/h local ventilation	2267	900
400 m³/h local ventilation	1600	635
50% source reduction	2080	832
90% source reduction	420	170

Source of 1000 mg/h is in Room 1. The desired concentrations are 500 µg/m³ in Room 1 and 250 µg/m³ in all other rooms.

The model predictions are in good agreement with the experimental data for these three experiments. Additional experiments for model verification are planned with emphasis on aerosol spray products on wet sources. Additional experiments are also planned to better define room-to-room airflows and sink effects.

USES

The model has a wide range of uses, including helping with the global design of buildings, analyzing existing IAQ problems, estimating exposure to indoor pollutants, and analyzing IAQ control options. The use of the model to analyze IAQ control options is demonstrated below.

The model can be used to rapidly analyze the effectiveness of various IAQ control options. The model permits elimination of ineffective options and concentrates on the more effective options. As an example of this application, consider a five-room building with a strong source in one room. The allowable pollutant concentration in the room with the source is 1000 µg/m³ and the allowable concentration in the other rooms is 250 µg/m³. The data for the example are: all rooms are identical with a volume of 100 m³; all airflow is through the HVAC, which provides 400 m³/h into each room (30% of which is outdoor air); the source strength is 1000 mg/h;

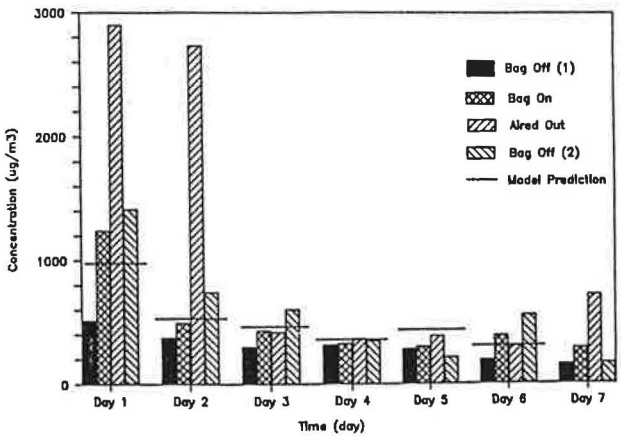

Figure 4 Perchlorethylene concentrations in closet from Tichenor et al. (1988)

there are no sinks; and the source is in room 1. The IAQ control options to be evaluated are:

1. Increase outside air to HVAC to 60% and 100%.
2. Allow local air exchange of 200 and 400 m^3/h in Room 1.
3. Use air cleaner with 50%, 70%, and 100% single-pass efficiency.
4. Reduce source strength by 50% and 90%.

The results of the model runs are shown in Table 4. Note that the only option that meets the concentration requirements for all rooms is the 90% source reduction. The air cleaner can meet the concentration requirements for all rooms except Room 1. The ventilation options do not meet the requirements for any of the rooms.

This example points out the importance of controlling the source and the general ineffectiveness of increasing general ventilation. The example also demonstrates that air cleaners can be effective in limiting the dispersion of pollutants through the HVAC system.

CONCLUSIONS

INDOOR is an easy-to-use tool for estimating pollutant distribution in a building. The model is in good agreement with experimental data. Additional research is needed to develop a library of default values of model input parameters. These defaults include source terms, sink terms, and room-to-room airflows under a wide range of conditions. Considerable additional work is also needed to better integrate exposure estimation with the overall model. At present, exposure must be estimated as a separate process.

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