Indoor Air 1996; 6: 259–270

ISSN 0905-6947

Managing Exposure to Indoor Air Pollutants in Residential and Office Environments

BRUCE A. TICHENOR[1,2] AND LESLIE E. SPARKS[1]

Abstract Sources of indoor air pollutants in residential and office environments can be managed to reduce occupant exposures. Techniques for managing indoor air pollution sources include: source elimination, substitution, modification, pretreatment, and altering the amount, location, or time of use. Intelligent source management requires knowledge of the source's emission characteristics, including chemical composition, emission rates, and decay rates. In addition, knowledge of mechanical and natural outdoor air exchange rates, heating/air-conditioning duct flow rates, and local exhaust fan (e.g., kitchen, bathroom) flow rates is needed to determine pollutant concentrations. Finally, indoor air quality (IAQ) models use this information and occupant activity patterns to determine instantaneous and/or cumulative individual exposure. This paper describes a number of residential and office scenarios for various indoor air pollution sources, several ventilation conditions, and typical occupant activity patterns. IAQ model predictions of occupant exposures for these scenarios are given for selected source management options. A one-month period was used to compare exposures; thus, long-term exposure information is not presented in this paper.

Key words Source emissions; Carpet; Aerosol; Latex paint; Furniture; VOC; Formaldehyde; IAQ models; Exposure; Source management; HVAC.

Received 17 May 1995. Accepted for publication 10 October 1995.

Introduction

Indoor air pollution, especially due to volatile organic compounds (VOCs), is primarily caused by emissions from indoor sources. The levels (concentrations) of these pollutants are affected by many factors, including: 1) the emission characteristics of the source (e.g., chemical composition, emission rate, decay rate); 2) the interaction of these emissions with interior surfaces (e.g., sink adsorption/desorption); 3) dilution and flushing by outdoor air exchange (assuming unpolluted outdoor air); and 4) processes designed to remove pollutants (e.g., local ventilation and air cleaners). Occupant exposure to indoor air pollution is a function of the temporal and spacial distribution of the pollutants and individual activity patterns.

The purpose of this paper is to explore options for reducing occupant exposure in residential and office environments by managing indoor air quality (IAQ). While air cleaning devices can be used to help manage IAQ (VanOsdell and Sparks, 1995), the focus of this paper is on management of sources of VOCs, including selection of high, medium, or low emitting sources. The *medium* emission factors used in this paper are based on reported data. The *high* and *low* emission factors were selected to cover a reasonable range of emissions for each source but are not based on source test data. Different emission factors may be achieved by source substitution, modification, or pretreatment. Source elimination may also be an option. Source management also includes selecting the amount used, the time of use, and the location of use. In addition, sources can be used with various air exchange rates and with or without local ventilation. The ventilation rates used in the following analyses cover the range expected under realistic conditions. Finally, occupant activity patterns ultimately dictate individual exposures.

The following analyses are provided to show how these various factors affect individual exposure to indoor air pollutants and how one can evaluate these exposures. The paper shows how available tools can be used to estimate exposures; it does not provide optimal solutions for minimizing exposure. As will be shown, the solutions for reducing exposures are dependent on specific scenarios and must be determined on a case-by-case basis. A one-month period was used to compare exposures; thus, long-term exposure information is not presented in this paper. However, the modeling techniques are applicable to long-term exposure scenarios. Also, while the paper deals exclusively with VOCs, other indoor pollutants (e.g., particles, combustion gases, biocontaminants, radon) can be

[1]*Indoor Environment Management Branch, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC 27711, Fax: (919)541-2157.* [2]*Current address: Consultant, Rt1-Box 302 C, Macon, NC 27551.*

managed via control of sources, ventilation (including humidity control) and occupant behavior.

Exposure Scenarios

An IAQ model has been developed to predict occupant exposure to indoor air pollutants based on source/sink behavior, ventilation parameters, and occupant activity patterns (Sparks et al., 1993). In this paper, the model was used to predict occupant exposures for several combinations of sources, sinks, ventilation scenarios, and activity patterns in both residential and office environments.

Residential Scenarios

Residential environment

A three-room, single-level residential environment was evaluated (see Figure 1). The forced air heating and cooling system has supply registers in the living area, bedroom, and bathroom; the return grille is in the hall. The bathroom has a separate exhaust fan.

Sources

Four typical indoor sources with a wide range of emission rates and decay rates were selected. Each source was assigned low, medium, and high emission factors.

Aerosol product – This product emits VOCs in short bursts during use; examples include personal care (e.g., hair spray) and cleaning (e.g., spot remover) products. The following total VOC (TVOC) emission factors were assumed: low=100 mg/use; medium=500 mg/use; and high=5000 mg/use.

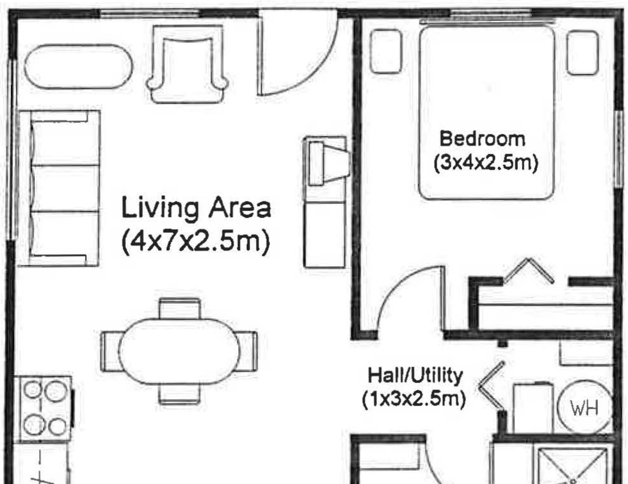

Fig. 1 Residence floor plan

Carpet - A carpet with styrene-butadiene-latex rubber backing emits VOCs, including 4-phenylcyclohexene (4-PC), with a first-order decay of the form:

$$EF=EF_0e^{-kt} \quad (1)$$

where, EF=emission factor ($mg/m^2 \cdot h$) at time t, EF_o=emission factor ($mg/m^2 \cdot h$) at time 0, k=first-order decay rate (h^{-1}), and t=time (h). The following initial emission factors (EF_o) were assumed: low=0.02 mg/$m^2 \cdot h$; medium=0.2 $mg/m^2 \cdot h$; and high=2 $mg/m^2 \cdot h$; and a single k value of 0.004 h^{-1} was used.

Latex paint – Water-based latex paint emits polar VOCs. Small dynamic chamber testing (Tichenor, 1995) showed that the TVOC emissions can be described by a second-order decay of the form:

$$EF=(EF_o)/(1+k_2EF_ot) \quad (2)$$

where, k_2=second-order decay rate constant. An initial emission factor (EF_o) of 80 $mg/m^2 \cdot h$ was used; and for low, medium, and high emissions, k_2 values of 0.006, 0.004, and 0.002 m^2/mg, respectively, were assumed.

A common ingredient of latex paint is Texanol®, which is used as a coalescing agent. Texanol® emissions were modeled by assuming that gas-phase mass transfer is the predominant mechanism (Tichenor et al., 1993):

$$EF=k_g[C_o(M/M_o)-C] \quad (3)$$

where, k_g=gas-phase mass transfer coefficient (m/h), C_o=concentration (mg/m^3) at the surface at time 0, M=emittable mass in the source (mg/m^2) at time t, and M_o=initial emittable mass (mg/m^2). The term "emittable mass" is used to describe the total mass of VOC (in this case, Texanol®) that can potentially be emitted from the source over time. Note that the emittable mass is not always equal to the total pollutant mass in the source. A mass transfer coefficient (k_g) of 3 m/h was assumed. High, medium, and low emissions were calculated based on values for C_o=40, 25, and 25 mg/m^3 and M_o=1200, 500, and 150 mg/m^2, respectively. The model coefficients for the medium emission rates are based on small chamber tests (Tichenor, 1995).

Cabinets – Cabinets manufactured from composite wood products emit formaldehyde. Mass transfer models (Foust et al., 1960; Tichenor et al., 1993) can be used to describe both short- and long-term formaldehyde emissions:

$$EF=k_s[C_o(M/M_s)-C] + k_l[C_o(M/M_l)-C] \quad (4)$$

where, k_s=short-term mass transfer coefficient (m/h), C_o=concentration of formaldehyde (mg/m^3) at the surface at time 0, M=mass of formaldehyde in the source (mg/m^2) at time t, M_s=short-term emittable mass (mg/m^2), C=concentration of formaldehyde (mg/m^3) at the surface at time t, k_l=long-term mass transfer coefficient (m/h), and M_l=long-term emittable mass (mg/m^2). Formaldehyde emissions data from large chamber testing of furniture (Mølhave et al., in press) were used to determine k_s=3 m/h, k_l=0.25 m/h, and the model coefficients shown in Table 1 for medium emissions. Coefficients for low and high emissions were estimated.

Source location and time of use – Table 2 shows the location of each source, including area, and the time the source was used or installed.

Sinks

Interior walls, ceilings, floors, and other surfaces (e.g., furnishings) were assumed to behave as indoor sinks exhibiting Langmuir sink behavior; i.e., at equilibrium:

$$Ck_a=M_sk_d \quad (5)$$

where, C=VOC concentration (mg/m^3), k_a=adsorption rate (m/h), M_s=VOC mass in sink (mg/m^2), and k_d=desorption rate (h^{-1}). For general sinks (walls, ceilings, non-carpet flooring and furnishings): k_a=0.1 m/h and k_d=0.1 h^{-1}; and for carpet: k_a=0.1 m/h and k_d=0.008 h^{-1} (Sparks et al., 1991). Table 3 provides sink information for the residential scenario.

Table 1 Coefficients for formaldehyde emission model

Magnitude of Emissions	C_o (mg/m^3)	M_s (mg/m^2)	M_l (mg/m^2)
Low	0.7	10	1000
Medium	0.9	50	5000
High	1.1	250	25000

Table 2 Residential sources - location and time of use

Source	Location (m^2)*				Time of Use
	Living Area	Bedroom	Hall/Utility	Bathroom	
Aerosol	NO	NO	NO	YES	6 a.m. Every Day
Carpet	28	12	3	NO	New on First Day
Latex Paint	52.5	35	17.5	25	See Painter in Table 4
Cabinets	30	NO	NO	10	New on First Day

* Numbers show source areas (in m^2).

Table 3 Residential sinks - location, type, and area

Location	Type	k_a (m/h)	k_d (h^{-1})	Area (m^2)
Living Area	General	0.1	0.1	160
	Carpet	0.1	0.008	28
Hall/Utility	General	0.1	0.1	40
	Carpet	0.1	0.008	3
Bedroom	General	0.1	0.1	100
	Carpet	0.1	0.008	12
Bathroom	General	0.1	0.1	80

Table 4 Residential occupant activity patterns

Occupant	Sources	Time	Location
Full-time 1	Paint, Carpet, Cabinets, Aerosol	12 a.m. - 6:30 a.m.	Bedroom
		6:30 a.m. - 7 a.m.	Bathroom
		7 a.m. - 10 p.m.	Living Area
		10 p.m. - 12 a.m.	Bedroom
Full-time 2	Aerosol	12 a.m. - 7 a.m.	Bedroom
		7a.m. - 10 p.m.	Living Area
		10 p.m. - 12 a.m.	Bedroom
Part-time	Paint, Carpet, Cabinets, Aerosol (User)	12 a.m. - 6 a.m.	Bedroom
		6 a.m. - 6:30 a.m.	Bathroom
		6:30 a.m. - 7:30 a.m.	Living Area
		7:30 a.m. - 6 p.m.	Outdoors
		6 p.m. - 10 p.m.	Living Area
		10 p.m. - 12 a.m.	Bedroom
Painter	Paint	8 a.m. - 12 p.m.	Living Area
		12 p.m. - 1 p.m.	Outdoors (Lunch)
		1 p.m. - 2 p.m.	Hall/Utility
		2 p.m. - 3 p.m.	Bedroom
		3 p.m. - 4 p.m.	Bathroom
Vacate Painting Day (Full-time After)		1st Day	Outdoors
	Paint	2nd Day & Beyond	Living Area

Occupant Activity Patterns

The activity patterns for five people and the sources to which they are exposed are given in Table 4. The *full-time 1* occupant never leaves the apartment, while the *part-time* occupant is gone every day from 7:30 a.m. to 6:00 p.m. Note that the part-time occupant is the user of the aerosol product. *Full-time 2* represents a full-time occupant who attempts to avoid exposure to the aerosol product by not entering the bathroom. The *painter* is in the apartment only on the first day. Finally, the last row in Table 4 represents a *full-time occupant who vacates the apartment during the first day* to avoid exposure to the initial paint emissions.

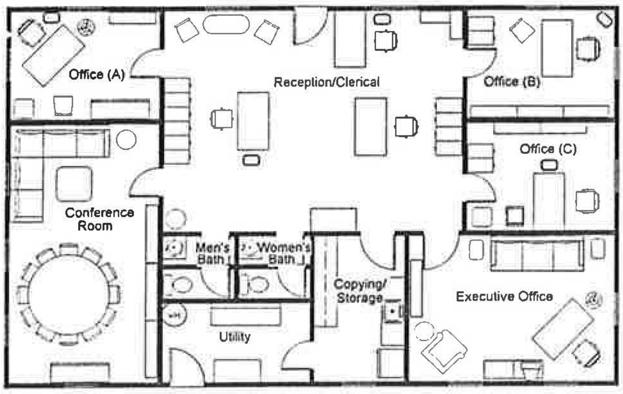

Fig. 2 Office floor plan

Ventilation and Air Movement
Three outdoor air exchange rates were assumed: high=2 ACH (air changes per hour); medium=0.5 ACH; and low=0.2 ACH. These values represent houses that range from "leaky" (2 ACH) to "tight" (0.2 ACH) and include the ventilation rate of 0.35 ACH recommended by ASHRAE Standard 62-1989 for residences (ASHRAE, 1989). The IAQ model is configured to distribute the outdoor air proportional to the room volumes. The outdoor air was assumed to contain no VOCs.

The heating/air-conditioning (HAC) fan distributed the air as follows: 350 m^3/h to the living area; 150 m^3/h to the bedroom; and 75 m^3/h to the bathroom. All the HAC air (575 m^3/h) was recirculated via the hall return. Note that the model provides for a mass balance of all flows, but does not include the heating or cooling effects of the HAC system. Some room-to-room air exchange (with no net flow) was also assumed to occur when the HAC fan was off: 70 m^3/h between the living area and hall; 30 m^3/h between the bedroom and hall; and 15 m^3/h between the bathroom and hall. An exhaust fan with a flow of 24 m^3/h to the outside was in the bathroom.

Office Scenarios

Office Environment
A 10-room, single-level commercial office environment was evaluated (see Figure 2). The building has a HVAC (heating, ventilating, and air-conditioning) system to supply outdoor air; outdoor air exchange also occurs through infiltration/exfiltration caused by leaks in the building envelope. Exhaust (airflow to the outdoors) is achieved through fans located in two bathrooms. All rooms have supply registers; the system return grille is located in the reception/clerical area.

Sources
Three sources were evaluated. Each source was assigned low, medium, and high emission factors.

Latex paint – The VOC and Texanol® emissions fron tex paint have been described earlier (see Equatio and 3). Several scenarios involving painting the con ence room are discussed below.

Furniture – Formaldehyde emissions from wooden fice furniture and cabinets are assumed to follow same model as the emissions from residential cabi discussed previously (see Equation 4). All rooms in office building, except the two bathrooms, are assu to have furniture or cabinets that emit formaldehyd

Wax – A petroleum-based wax product that emits V is assumed to be used by the janitorial staff to clean polish furniture. The gas-phase mass transfer model scribed by Equation 3 can be used to describe the V emissions. The following values were used: k_g=3 m C_o=16, 18, and 20 mg/m^3; and M_o=2000, 4000, and 8 mg/m^2 for low, medium, and high emissions, res tively.

Source location – Table 5 shows the location and are each source and the room dimensions.

Sinks
Sink behavior of interior surfaces was assumed to be same as for the residential environment. Carpeted flc were assumed, except for the two bathrooms, the co storage room, and the utility room. Table 6 provi sink information for the office scenario.

Occupant Activity Patterns
The occupant activity patterns for four people given in Table 7. The office *receptionist* represent full-time employee. The *client* is a one-time visitor w attends a meeting in the conference room. The *jan* works evenings, and the *painter* is only in the cont

Table 5 Office source locations and areas, plus room dimensions

Location	Source Area (m^2)			Room Dimensions	
	Paint	Furniture	Wax	Length	Widt
Reception/ Clerical	0	40	15	8	6
Office (A)	0	15	3	4	3
Office (B)	0	25	3	4	3
Office (C)	0	20	3	4	3
Executive Office	0	20	4	5.5	4
Copying/Storage	0	10	0	4	2.5
Utility	0	5	0	4	2
Men's Bathroom	0	0	0	2	2
Women's Bathroom	0	0	0	2	2
Conference Room	50	30	8	7	4

Table 6 Office sinks - location, type, and area

Location	Type	k_a (m/h)	k_d (h^{-1})	Area (m^2)
Reception/ Clerical	General	0.1	0.1	300
	Carpet	0.1	0.008	48
Office (A)	General	0.1	0.1	100
	Carpet	0.1	0.008	12
Office (B)	General	0.1	0.1	100
	Carpet	0.1	0.008	12
Office (C)	General	0.1	0.1	100
	Carpet	0.1	0.008	12
Executive Office	General	0.1	0.1	140
	Carpet	0.1	0.008	22
Copying/Storage	General	0.1	0.1	80
Utility	General	0.1	0.1	70
Men's Bathroom	General	0.1	0.1	50
Women's Bathroom	General	0.1	0.1	50
Conference Room	General	0.1	0.1	150
	Carpet	0.1	0.008	28

ence room for the time required to paint the walls with latex paint.

Ventilation and Air Movement

The HVAC system flows are shown in Table 8. Under normal operation, the HVAC system was assumed to cycle *on* from 8 a.m. to 5 p.m. Monday through Friday and *off* the rest of the time. Thus, no HVAC flows occurred during normal weekends. When the system was off, no inter-room air movement was assumed. In addition to the ventilation air supplied by the HVAC system (0.5 ACH), infiltration/exfiltration caused by building leakage was assumed to occur at three levels: high=1 ACH, medium=0.3 ACH, and low=0.1 ACH. These values represent a range of "leaky" (1 ACH) to "tight" (0.1 ACH) commercial buildings (Persily, 1989). The total outside air supplied by mechanical ventilation and infiltration (@ 0.5 ACH) provides sufficient ventilation according to ASHRAE (1989) for the offices (20 cfm/occupant) and the reception area (4 occupants at 15 cfm/occupant); the conference room has only enough outside air for 2 occupants at 20 cfm/occupant. As with the residential scenario, the model provides for a mass balance of all flows, but does not include the heating or cooling effects of the HVAC system.

Table 8 Office HVAC flows (m3/h)

Location	Supply	Return	Exhaust
Outdoors	0	200	0
Reception/Clerical	500	1600	0
Office (A)	150	0	0
Office (B)	150	0	0
Office (C)	150	0	0
Executive Office	200	0	0
Copying/Storage	150	0	0
Utility	100	0	0
Men's Bathroom	50	0	100
Women's Bathroom	50	0	100
Conference Room	300	0	0
Total	1800	1800	200

Exposure Parameters

By combining occupant activity patterns with concentration/time profiles, occupant exposure to source emissions can be estimated. Occupant exposures to indoor air pollutants can result in various types of health effect, including: long-term chronic problems, short-term acute or toxic effects, and a range of irritation and odor responses (e.g., Sick Building Syndrome). The cause and effect relationships between indoor exposure and health effects are not well understood and are beyond the scope of this paper. On the other hand, relevant exposure parameters can be calculated. Health effects can be due to cumulative total exposure, which is calculated for an occupant by multiplying the concentration to which the person is exposed by the exposure time. Health effects may also be a function of the maximum concentration to which an occupant is exposed. For example, the Threshold Limit Value-Ceiling (TLV-C) is defined as a concentration that should not be exceeded (ACGIH, 1988). Irritation and odor responses occur at threshold levels and can be evaluated by determining the length of time an occupant is exposed to concentrations exceeding the odor or irritation threshold level (Wolkoff and Nielsen, 1993). Thus, sources can be evaluated by three different exposure parameters that are related to relevant health effects: 1) cumulative exposure [(mg/m^3)h]; 2) maximum concentration (mg/m^3); and 3) time exposed to concentrations exceeding odor or irritation threshold levels (h).

Table 7 Office occupant activity patterns

Occupant	Sources	Day(s)	Time	Location
Receptionist	Paint, Wax, Furniture	Monday thru Friday	9 a.m. - 5 p.m.	Reception/Clerical
Client	Paint, Wax, Furniture	Tuesday	9 a.m. - 12 p.m.	Conference Room
			12 p.m. - 1 p.m.	Outdoors
			1 p.m. - 5 p.m.	Conference Room
Janitor	Paint, Wax, Furniture	Monday thru Friday	8 p.m. - 10 p.m.	A, B, C, and Executive Offices
			10:00-10:20 p.m.	Conference Room
			10:20 p.m. - 12 a.m.	Reception/Clerical
Painter	Paint	Saturday or Monday	9a.m. - 12 p.m.	Conference Room

Odor or Irritation Threshold Levels

For the sources described above for residential and office environments, odor or irritation thresholds (O/ITs) were assumed for each source:

A) *Aerosol product (residence)* – Two O/IT levels were assumed for TVOC exposure: high threshold=3 mg/m^3; and low threshold=0.3 mg/m^3. These TVOC threshold values were selected based on recommendations of several authors. Woods et al. (1993) recommend that continuous exposure to TVOC (such as toluene) be limited to concentrations of 0.5 mg/m^3 for "Maximum Acceptability" and to 3.0 mg/m^3 for "80% Acceptability." Skåret (1993) recommends a TVOC level of 0.3 mg/m^3 as a "practical target". Rengholt (1993) suggests TVOC levels of 0.2 and 0.5 mg/m^3 for 10% and 20% occupant dissatisfaction, respectively. Gilbert et al. (1993) describe a program of using "low emission materials" to achieve indoor TVOC concentrations of 0.3 – 0.5 mg/m^3.

B) *Carpet (residence)* – A single O/IT level was assumed for TVOC exposure: low threshold=0.01 mg/m^3. This threshold is based on an odor threshold of 1 ppb for 4-phenylcyclohexene (4-PC) and assumes that two-thirds of the TVOC is 4-PC.

C) *Latex paint (residence and office)* – The high O/IT was assumed to be 3 mg/m^3 TVOC. The low O/IT was assumed to be 0.46 mg/m^3 of Texanol®, based on half of the odor detection limit for Texanol® of 0.91 mg/m^3 (Wolkoff and Nielsen, 1993).

D) *Cabinets (residence) and furniture (office)* - The low irritation threshold for cabinets and furniture was set at 0.125 mg/m^3 formaldehyde, based on an irritation threshold of 0.1 ppm for formaldehyde. This is also considered the "concentration of concern" by the World Health Organization (WHO, 1985).

E) *Wax (Office)* – Two O/IT levels were assumed for TVOC exposure: high threshold=3 mg/m^3; and low threshold=0.3 mg/m^3.

Predicted Occupant Exposures

Residential Exposures

IAQ model predictions of residential occupant exposures over a 30-day period were made for various combinations of source emission rates, ventilation scenarios (including local exhaust), and occupant activity patterns. Figures 3–8 show the time history of the TVOC and formaldehyde concentrations due to emissions from the four sources at medium emission rates, outdoor air exchange rate=0.5 ACH, the HAC fan on, and the bathroom exhaust fan off. Figure 3 presents the predictions for all four sources showing that the TVOC concentrations range from <0.1 to >50 mg/m^3, depending on the source and time. This plot shows the effect of each source individually, not the combined effect of all

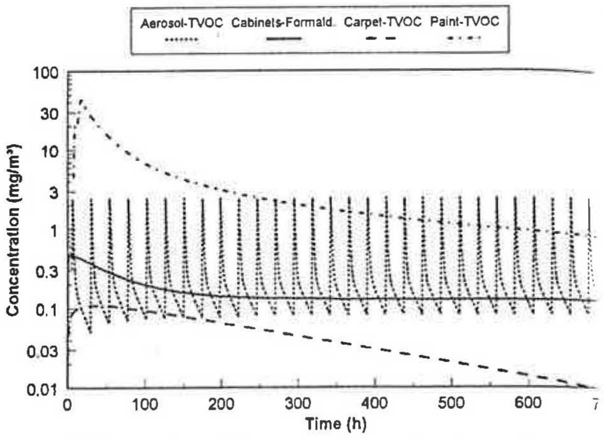

Fig. 3 TVOC and formaldehyde concentrations in residence li
area due to four sources

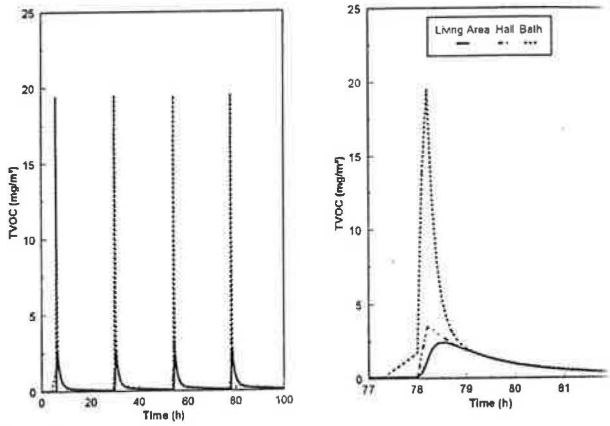

Fig. 4 TVOC concentrations in residence due to aerosol product

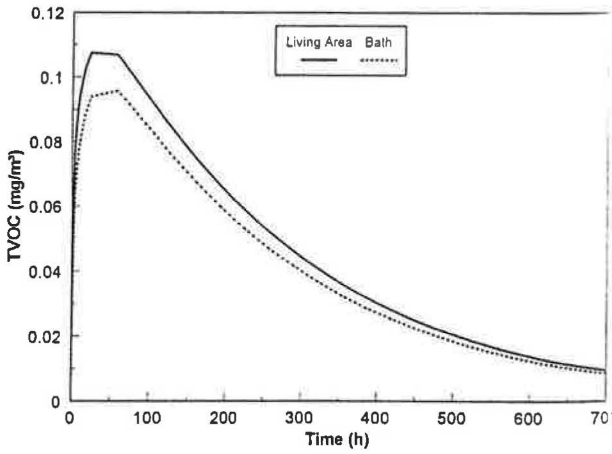

Fig. 5 TVOC concentrations in residence due to carpet

the sources. Figure 4a shows the TVOC concentratio
due to the aerosol product over the first 100 hours, a
Figure 4b shows the impact of a single use on thr
rooms. Figure 5 shows the TVOC concentrations in t
living area and bathroom due to carpet emission. Fi
ures 6 and 7 present the concentrations of TVOC a

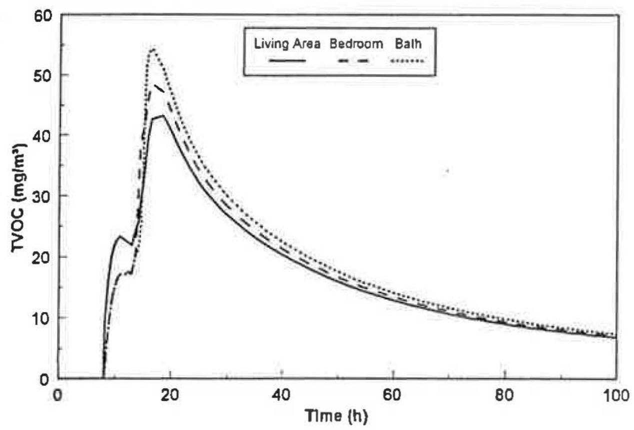

Fig. 6 TVOC concentrations in residence due to latex paint

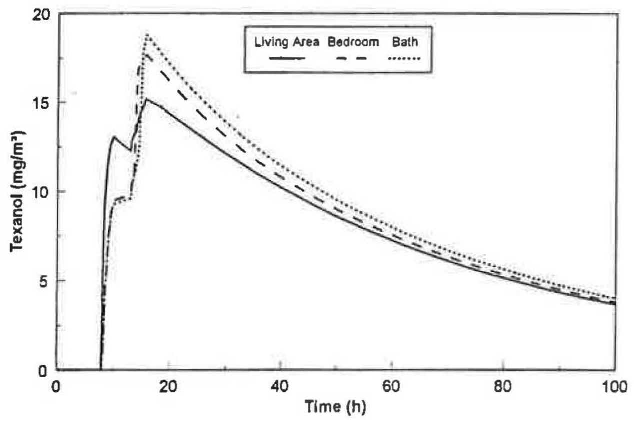

Fig. 7 Texanol® concentrations in residence due to latex paint

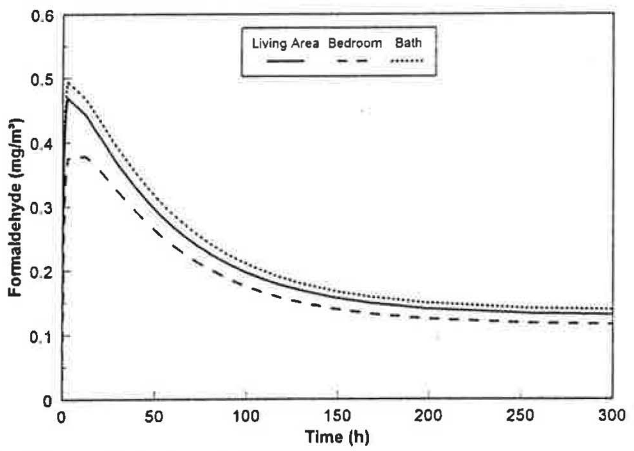

Fig. 8 Formaldehyde concentrations in residence due to cabinets

Texanol®, respectively, over the first 100 hours in three rooms due to latex paint emissions. The sudden changes in the curves of Figures 6 and 7 are due to the painter's one-hour break for lunch (see Table 4). Figure 8 shows the formaldehyde concentrations for the first 300 hours in three rooms due to emissions from cabinets.

Tables 9–11 present the results of IAQ model analyses

Table 9 Effect of emission rate on residential exposure (full-time occupant, ventilation=0.5 ACH)

Source	Emission Rate	Total Expos. [(mg/m^3)h]	Max. Conc. (mg/m^3)	Time (h) >High I/OT*	Time (h) > Low I/OT
Aerosol	High	2450	66	134	721
	Medium	245	6.6	9	134
	Low	49	1.3	0	31
Carpet	High	327	1.1	-	727
	Medium	33	0.1	-	684
	Low	3.3	0.01	-	66
Paint	High	4990	58	382	386
	Medium	2870	44	199	235
	Low	2050	37	142	88
Cabinets	High	219	0.7	-	727
	Medium	110	0.5	-	529
	Low	69	0.3	-	33

*I/OT=Irritation/Odor Threshold

Table 10 Effect of occupant activity patterns on residential exposure (medium emission rate, ventilation=0.5 ACH)

Source	Occupant	Total Expos. [(mg/m^3)h]	Max. Conc. (mg/m^3)	Time>Hi I/OT (h)	Time>Lo I/OT (h)
Aerosol	Full-time	245	7	9	134
	Part-time (user)	250	15	14	45
Carpet	Full-time	33	0.1	-	684
	Part-time	18	0.1	-	387
Paint	Full-time	2870	44	199	235
	Part-time	1610	44	108	131
	Painter	182	53	7	7
	Vacate 1 Day	2310	34	183	217
Cabinets	Full-time	110	0.5	-	529
	Part-time	60	0.5	-	214

Table 11 Effect of ventilation rates on residential exposure (medium emission rate, full-time occupant)

Source	Ventilation Rate (ACH)	Total Expos. [(mg/m^3)h]	Max. Conc. (mg/m^3)	Time (h) > High I/OT	Time (h) > Low I/OT
Aerosol	0.2	591	8	15	705
	0.5	245	7	9	134
	2	58	4	5	36
Carpet	0.2	80	0.2	–	727
	0.5	33	0.1	–	684
	2	8	0.03	–	324
Paint	0.2	7110	67	527	587
	0.5	2870	44	199	235
	2	712	16	46	70
Cabinets	0.2	217	0.6	–	727
	0.5	110	0.5	–	529
	2	30	0.3	–	24

Table 12 Effect of local exhaust on residential exposure to VOCs from aerosol product (medium emission rate, ventilation=0.5 ACH)

Bath Fan	HAC Fan	Occupant	Total Expos. [(mg/m^3)h]	Max. Conc. (mg/m^3)	High I/OT	Time (h) > Low I/OT
On	On	Part-time (user)	164	9	13	34
		Full-time 1	159	5	0	31
		Full-time 2	154	1	0	31
On	Off	Part-time (user)	121	12	13	14
		Full-time 1	25	3	2	16
		Full-time 2	0	0	0	0
Off	On	Part-time (user)	250	15	13	45
		Full-time 1	245	7	9	134
		Full-time 2	218	2	0	134
Off	Off	Part-time (user)	209	14	13	25
		Full-time 1	169	4	5	20
		Full-time 2	137	0.4	0	11

of various residential exposure scenarios over a 30-day period for the four sources and three exposure parameters discussed above (i.e., total exposure, maximum concentration, time exposed to concentrations exceeding the high odor or irritation threshold, and time exposed to concentrations exceeding the low odor or irritation threshold). Table 9 shows how changing the emission rate affects exposure; Table 10 highlights the effect of cupant activity; and Table 11 illustrates the influence natural ventilation (i.e., dilution and flushing with o door air). Table 12 shows the impact of local exha (bathroom fan) and air movement (HAC fan). Both fa were assumed to be on or off for the complete 30-day riod.

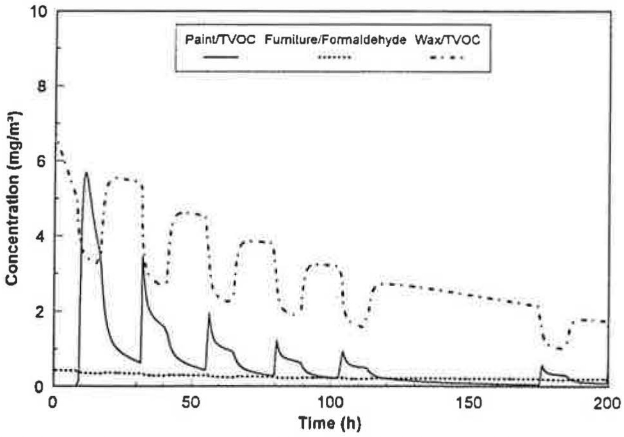

Fig. 9 TVOC and formaldehyde concentrations in office reception/clerical area due to three sources

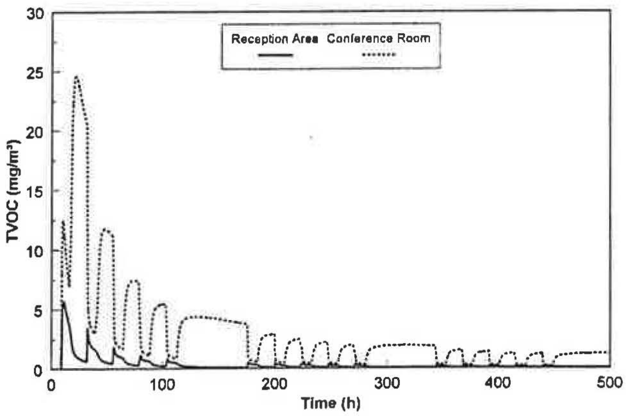

Fig. 10 TVOC concentrations in office due to latex paint

Discussion of Residential Exposures

Tables 9–12 show that the effectiveness of various IA management options (e.g., changing emission rates, d ferent occupant activities, and various ventilation s narios) is dependent on the exposure parameter of terest. For example, reducing the emission rate (Table and increasing the air exchange rate (Table 11) both duce cumulative total exposure and the maximum co centration, but the duration of exposure to odor or ir tation thresholds may not change as much. The resu also show how interactions between various factors c affect exposure. For example, Table 10 shows how pro uct users (painter and aerosol user) can be exposed high maximum concentrations due to locations a times of use. The results for these products also sho that non-users can experience high total exposure ev though they are exposed to much lower concentratio than the user. The strategy of vacating for 1 day duri painting can reduce cumulative exposure and ma mum concentration exposure by about 20%. The int action of local exhaust with HAC systems is shown Table 12 where the person who does not enter the bat room (Full-time 2) is completely isolated from exposu and is never exposed to the high irritation or od threshold concentration when the bathroom fan is and the HAC fan is off.

Office Exposures

IAQ model predictions of office occupant exposur over 4 weeks were made for various combinations

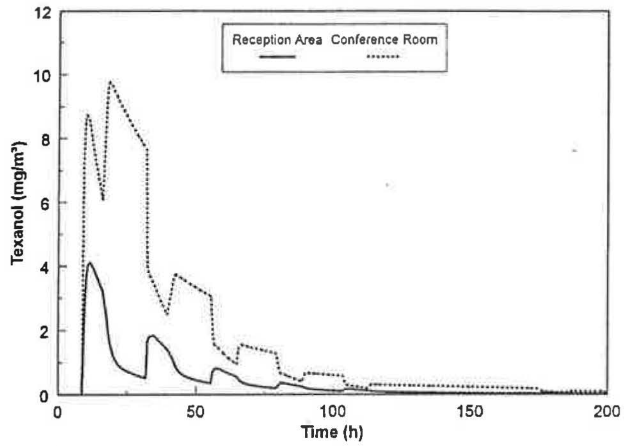

Fig. 11 Texanol® concentrations in office due to latex paint

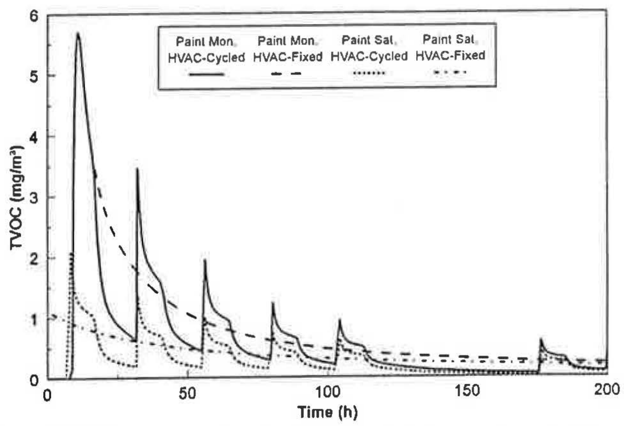

Fig. 12 TVOC concentrations in office due to latex paint applied Saturday or Monday with HVAC system cycling or fixed on

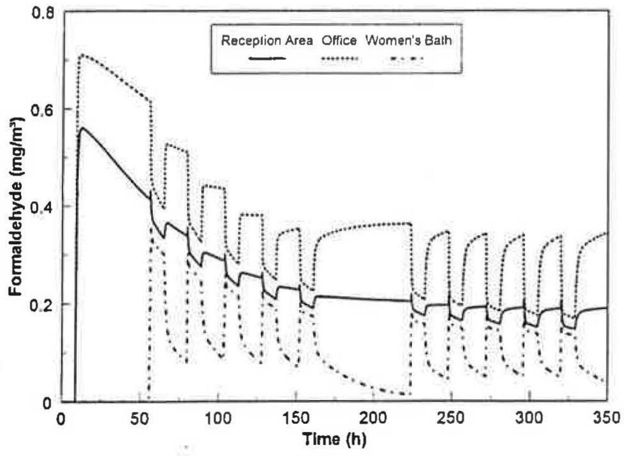

Fig. 13 Formaldehyde concentrations in office due to cabinets

source emission rates, HVAC operating scenarios, and occupant activity patterns. Figures 9–14 show the time history of the TVOC, Texanol®, and formaldehyde concentrations due to emissions from the three office sources at medium emission rates and natural air exchange rate=0.3. Except for Figure 12, the HVAC system

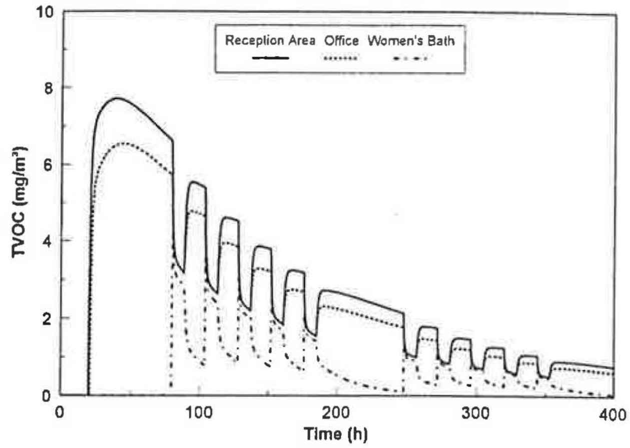

Fig. 14 TVOC concentrations in office due to wax

was assumed to cycle normally. Figure 9 presents the predictions, starting at 12 a.m. Monday, for the first 200 hours in the reception/clerical area for all three sources. This plot shows the effect of each source individually, not the combined effect of all the sources. The sources were used/installed as follows: latex paint – 9 a.m. Monday; furniture/cabinets – 9 a.m. on the previous Saturday; and wax – 8 p.m. on the previous Friday. Note the influence of the HVAC system on the temporal behavior of the concentrations. Figures 10 and 11 present the concentrations of TVOC and Texanol®, respectively, over the first 500 and 200 hours in two rooms due to latex paint emissions. Note the higher concentrations in the conference room, where the paint was applied. Figure 12 shows the influence of HVAC operating scenarios for paint applied either Saturday (Sat.) or Monday (Mon.) morning. The graph starts at 12 a.m. Monday and shows how TVOC concentrations vary, depending on whether the HVAC operated normally (cycled) or was turned on for the full 4 weeks (fixed). Figure 12 presents predictions of TVOC concentration for the reception/clerical area for the first 200 hours. Figure 13 shows the formaldehyde concentrations for the first 350

Table 13 Effect of emission rate on office exposure (receptionist, normal HVAC operation, infiltration=0.3 ACH)

Source	Emission Rate	Total Expos. [(mg/m³)h]	Max. Conc. (mg/m³)	Time (h) > High I/OT	Time (h) > Low I/OT
Paint	High	144	7	11	39
	Medium	90	6	7	24
	Low	67	5	6	7
Furniture Cabinets	High	59	0.6	–	160
	Medium	28	0.4	–	160
	Low	16	0.2	–	11
Wax	High	284	5.3	35	152
	Medium	142	4.6	9	90
	Low	62	2.7	0	47

Table 14 Effect of occupant activity patterns on residential exposure (medium emission rate, normal HVAC operation, infiltration=0.3 ACH)

Source	Occupant	Total Expos. [(mg/m³)h]	Max. Conc. (mg/m³)	Time> Hi I/OT (h)	Time>Lo I/OT (h)
Paint	Receptionist	90	6	7	24
	Client	24	4	5	7
	Janitor	38	25	12	9
	Painter	34	12	3	3
Furniture/ Cabinets	Receptionist	28	0.4	–	160
	Client	3	0.4	–	7
	Janitor	22	0.5	-	80
Wax	Receptionist	142	4	9	190
	Client	19	13	2	7
	Janitor	126	6	18	57

Table 15 Effect of natural ventilation rate on office exposure (receptionist, medium emission rate, normal HVAC operation)

Source	Infiltration (ACH)	Total Expos. [(mg/m³)h]	Max. Conc. (mg/m³)	Time (h) >High I/OT	Time (h) > Low I/OT
Paint	0.1	151	7	11	39
	0.3	89	6	7	24
	1.0	41	4	6	7
Furniture Cabinets	0.1	43	0.5	–	160
	0.3	28	0.4	–	160
	1.0	12	0.2	–	11
Wax	0.1	283	5.3	35	152
	0.3	142	4.6	9	90
	1.0	51	2.7	0	47

hours, starting at 12 a.m. Saturday, in three rooms due to emissions from furniture and cabinets. Figure 14 presents the TVOC concentrations, starting at 12 a.m. on Friday, in three rooms due to wax emissions.

Tables 13–15 present the results of IAQ model analyses of various office exposure scenarios for the t! sources used/installed as follows: latex paint – 9 , Monday; furniture/cabinets – 9 a.m. on the previ Saturday; and wax – 8 p.m. on the previous Friday. ble 13 shows how changing the emission rate affects posure, Table 14 highlights the effect of occupant ac ity, and Table 15 illustrates the influence of natural v tilation (in addition to the 0.5 ACH provided by HVAC system when it is on). Table 16 shows how ex sures to paint emissions are affected by the day of pa ing (Saturday or Monday) and the operation of HVAC system (cycled normally or fixed in the "on" sition). Table 17 indicates how exposures to wax er sions are affected by the night of use (Friday or M day) and whether the HVAC system is cycled norm or fixed "on". Table 18 illustrates how changing HVAC operation and/or installing the furniture 1 (weeks earlier can affect the occupant's exposures to i maldehyde. The results reported in Tables 13 – 18 sumed 28 days of exposure starting at 12 a.m. Mond.

Discussion of Office Exposures

Tables 13–18 provide information on how various I. management options (i.e., varying emission rates, (ferent occupant activities, altering ventilation, a changing the time of application/installation) affect fice occupant exposures. For example, reducing emission rate (Table 13) and increasing the air exchar rate (Table 15) both reduce cumulative total exposu and the maximum concentration, but the duration exposure to odor or irritation thresholds may r change significantly (e.g., the time exposed to the fo maldehyde threshold does not change between n dium and high emission rates and medium and low , exchange rates). The results also show how interactic

Table 16 Effect of painting day and HVAC operation on office exposure to paint emissions (medium emission rate, infiltration=0.3 ACH)

Paint Day	HVAC Oper.	Occupant	Total Expos. [(mg/m³)h]	Max. Conc. (mg/m³)	Time (h) > High I/OT	Time (h) > Low I/OT
Mon.	Cycled	Receptionist	89	6	7	24
		Client	22	5	4	7
		Janitor	38	25	2	9
		Painter	33	13	3	3
Mon.	Fixed ON	Receptionist	77	6	7	15
		Client	19	3	0	7
		Janitor	35	5	0	8
		Painter	33	13	3	3
Sat.	Cycled	Receptionist	46	2	0	16
		Client	10	2	0	7
		Janitor	19	6	1	2
		Painter	121	56	3	3
Sat.	Fixed ON	Receptionist	32	1	0	0
		Client	7	1	0	0
		Janitor	18	1	0	0
		Painter	33	13	3	3

Table 17 Effect of waxing night and HVAC operation on office exposure to wax emissions (medium emission rate, infiltration=0.3 ACH)

Wax Night	HVAC Oper.	Occupant	Total Expos. [(mg/m^3)h]	Max. Conc. (mg/m^3)	Time (h) > High I/OT	Time (h) > Low I/OT
Fri.	Cycled	Receptionist	142	4	9	90
		Client	21	3	2	7
		Janitor	118	6	16	57
Fri.	Fixed ON	Receptionist	84	3	0	62
		Client	15	2	0	7
		Janitor	48	3	1	38
Mon.	Cycled	Receptionist	176	5	22	103
		Client	28	5	7	7
		Janitor	149	7	17	59
Mon.	Fixed ON	Receptionist	123	4	16	70
		Client	28	4	7	7
		Janitor	68	4	5	42

Table 18 Effect of installation time and HVAC operation on office exposure to formaldehyde from furniture (medium emission rate, infiltration=0.3 ACH)

Install Time	HVAC Oper.	Occupant	Total Expos. [(mg/m^3)h]	Max. Conc. (mg/m^3)	Time (h) >0.125 mg/m^3
Sat.	Cycled	Receptionist	28	0.4	160
		Client	3	0.4	7
		Janitor	21	0.5	76
Sat.	Fixed ON	Receptionist	19	0.3	139
		Client	2	0.3	7
		Janitor	11	0.3	19
One Week Earlier	Cycled	Receptionist	23	0.2	153
		Client	1	0.2	7
		Janitor	19	0.3	76
One Week Earlier	Fixed ON	Receptionist	17	0.1	0
		Client	1	0.1	0
		Janitor	9	0.1	1
Four Weeks Earlier	Cycled	Receptionist	21	0.2	85
		Client	1	0.2	7
		Janitor	18	0.3	76

between various factors can affect exposure. For example, Table 14 indicates that the janitor is exposed to the highest concentration for both wax and paint under normal HVAC operation. This occurs because the concentration in the conference room, where paint was used, increases after the HVAC system is turned off, thus exposing the night-time janitor to elevated VOC levels in that room. Tables 16–18 provide insight into the interaction of time of product use and HVAC system operation. Exposure reductions are achieved by delaying occupant exposure and by continuous operation of the HVAC system. The effects of these actions vary depending on the occupant, the source, and the exposure parameter. For example, the strategy of painting on Saturday rather than on Monday has a greater effect than changing the operation of the HVAC system (Table 16). On the other hand, earlier installation of furniture is not as effective as continuous HVAC operation in reducing formaldehyde exposure (Table 18) due to the slow decay of the formaldehyde emissions.

Conclusions

The results presented in this paper show that exposure to indoor pollutants is a complex function of many parameters. Because of the many factors involved in controlling individual exposure, it is impossible to provide a general answer to the question – "What is the best way to reduce exposure to indoor air pollution?" The answer depends on the exposure scenario.

Individual exposures to indoor air pollutants are affected by source emission characteristics, source use scenarios, occupancy patterns, and ventilation options. Source management options that alter these parameters can dramatically affect exposures. The effectiveness of IAQ management depends on the type of exposure (i.e., cumulative, maximum concentration, or duration above a threshold) reduction desired. Interactions between the various parameters make it necessary to examine the effect of all relevant factors before drawing any conclusions regarding the effectiveness of IAQ management vis-à-vis exposure. IAQ models provide the tools for examining the scenarios of interest and allow selection of the most effective option.

Although costs are not considered in this paper, it is recognized that the cost of an IAQ control strategy is an important consideration. Costs, like exposure, are scenario-dependent. IAQ models can be used with relevant cost information (i.e., capital costs of increased ventilation, cost of energy, and retrofit costs) to examine the scenarios of interest. The results from such analyses can then be used to estimate the costs of appropriate IAQ control strategies.

References

ACGIH (1988) *Threshold Limit Values and Biological Exposure Indices*, Cincinnati, OH, American Conference of Governmental Industrial Hygienists.

ASHRAE (1989) *Ventilation for Acceptable Indoor Air Quality*, Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE Standard 62-1989).

Foust, A., Wenzel, L., Clump, C., Maus, L. and Anderson, L. (1960) *Principles of Unit Operation*, New York, John Wiley and Sons.

Gilbert, D., Dingle, P. and Bentley, K. (1993) "A national strategy for internal environmental health in Australia". In: *Proceedings of Indoor Air '93*, Helsinki, International Conference on Indoor Air Quality and Climate, Vol. 3, pp. 577–572.

Mølhave, L., Dueholm, S. and Jensen, L.K. "Health assessment and risk evaluation of emissions from furniture: a case study", *Indoor Air* (in press).

Persily, A. (1989) "Ventilation rates in office buildings". In: *Proceedings of IAQ 89: The Human Equation: Health and Comfort*, Atlanta, GA, ASHRAE, pp. 128–136.

Rengholt, U. (1993) "Quality assured indoor climate qua (QA-ICQ)". In: *Proceedings of Indoor Air '93*, Helsinki, In national Conference on Indoor Air Quality and Clim, Vol. 3, pp. 519–524.

Skåret, E. (1993) "Indoor climate - air quality strategy guideline". In: *Proceedings of Indoor Air '93*, Helsinki, In national Conference on Indoor Air Quality and Clim, Vol. 3, pp. 513–518.

Sparks, L.E., Tichenor, B.A. and White, J.B. (1993) "Model individual exposure from indoor sources". In: Nagda, N (ed.) *Modeling of Indoor Air Quality and Exposure*, Phila phia, PA, ASTM, pp. 245–256 (ASTM Publication STP 12

Sparks, L.E., Tichenor, B.A., White, J.B. and Jackson, M (1991) "Comparison of data from an IAQ test house w predictions of an IAQ computer model", *Indoor Air*, 1 577–592.

Tichenor, B.A. (1995) "Evaluation of emissions from la paint". Paper presented at *Low- and No-VOC Coating Te nologies 2nd Biennial International Conference*, Durham, N U.S. Environmental Protection Agency.

Tichenor, B.A., Guo, Z. and Sparks, L.E. (1993) "Fundamen mass transfer model for indoor air emissions from surf coatings", *Indoor Air*, 3, 263–268.

VanOsdell, D.W. and Sparks, L.E. (1995) "Carbon adsorpt for indoor air cleaning", *ASHRAE Journal*, **37**(2), 34–40.

Wolkoff, P., and Nielsen, P. (1993) *Indoor Climate Labeling Building Materials - Chemical Emission Testing, Modeling, Indoor Relevant Odor Thresholds*, Copenhagen, National In tute of Occupational Health.

Woods, J.E., Arora, S., Sensharma, N.P. and Olesen, B. (1993) "Rational building performance and prescriptive teria for improved indoor environmental quality". In: *P ceedings of Indoor Air '93*, Helsinki, International Confere on Indoor Air Quality and Climate, Vol. 3, pp. 471–476.

World Health Organization (1985) *Indoor Air Quality Resear* Copenhagen, WHO Regional Office for Europe (EURO R ports and Studies 103).