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Volatile Organic Compound Concentrations and Emission Rates in New Manufactured and Site-Built Houses

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Abstract Concentrations of 54 volatile organic compounds (VOCs) and ventilation rates were measured in four new manufactured houses over 2–9.5 months following installation and in seven new site-built houses 1–2 months after completion. The houses were in four projects located in hot-humid and mixed-humid climates. They were finished and operational, but unoccupied.

Ventilation rates ranged from 0.14–0.78 h^{-1}. Several of the site-built houses had ventilation rates below the ASHRAE recommended value. In both manufactured and site-built houses, the predominant airborne compounds were α-pinene, formaldehyde, hexanal, and acetic acid. Formaldehyde concentrations were below or near 50 ppb with a geometric mean value for all houses of 40 ppb. Similarities in the types of VOCs and in VOC concentrations indicated that indoor air quality in the houses was impacted by the same or similar sources. Major identified sources included plywood flooring, latex paint and sheet vinyl flooring.

One site-built house was operated at ventilation rates of 0.14 and 0.32 h^{-1}. VOC emission rates calculated at the two conditions agreed within ±10% for the most volatile compounds. Generally, the ratios of emission rates at the low and high ventilation rates decreased with decreasing compound volatility. Changes in VOC emission rates in the manufactured houses over 2–9.5 months after installation varied by compound. Only several compounds showed a consistent decrease in emission rate over this period.

Key words Houses; Ventilation; Formaldehyde; Aldehydes; VOC; Emissions.

Practical Implications

The concentrations and emission rates of volatile organic compounds (VOCs) including formaldehyde were similar among a set of four new manufactured houses and seven new site-built houses. These similarities probably reflect the general similarities in materials and building practices used for single-family house construction. Elevated emission rates of a number of the predominant VOCs persisted over a period of at least 9 months. Some of these compounds have objectionable odors or are strong sensory irritants, such as formaldehyde. Concentrations of VOCs in new houses are probably best controlled by providing adequate, but not excessive ventilation, and by substitution of lower emitting materials.

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Introduction

Indoor sources of volatile organic compounds (VOCs) are a determinant of indoor air quality in houses. Many materials used to construct and finish the interiors of new houses emit VOCs including formaldehyde. These VOC emissions can result in substantial contamination of indoor air. It is recognized that such contamination is a probable cause of acute health effects and discomfort among occupants (Andersson et al., 1997).

Data on the impacts of VOC sources in houses currently being built in North America are needed, as historical data may be outmoded. Formaldehyde concentrations in manufactured houses serve as an example. Concentrations in excess of 0.1 ppm were frequently encountered in manufactured houses built a decade or more ago (National Research Council, 1981; Sexton et al., 1986, 1989). Today, less plywood paneling is used to finish the interiors of these houses. Also, the emissions of formaldehyde from wood products are generally lower (Kelly et al., 1999). Consequently, formaldehyde concentrations in contemporary manufactured houses may be lower than historical values. There have been other changes in the products and materials used in the construction of houses of all types, which may impact VOC concentrations. Examples include the increased use of engineered wood products and adhesives and the reformulation of paints.

Ventilation is another determinant of indoor air

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quality in houses. Ventilation serves as the primary mechanism for removal of gaseous contaminants generated indoors. Thus, higher contaminant concentrations are expected at lower ventilation rates given constant emission rates. The trend in new construction, supported by governmental programs, is to make house envelopes tighter. This practice improves energy efficiency by decreasing the infiltration of unconditioned outdoor air. Consequently, ventilation rates in new houses without supplemental ventilation can be relatively low with a related potential for degraded indoor air quality.

This study was conducted with the primary objective of characterizing and comparing the airborne concentrations and the emission rates of total VOCs and selected individual VOCs, including formaldehyde, among a limited number of new manufactured and site-built houses. Secondarily, the study attempted to identify the sources of specific VOCs and evaluate the effectiveness of several source substitution treatments for reducing concentrations of VOCs.

Material and Methods

Descriptions of Study Houses

Four manufactured and seven site-built houses were included in the study. They were located in the eastern and southeastern United States in hot-humid and mixed-humid climates.

The manufactured houses were produced by a single facility in Florida. In their construction and level of finish, they were generally representative of better-quality two-section houses sold in that state. They were manufactured in July 1997 and, within three weeks, were installed at a nearby sales center. Air sampling was initially conducted on 9/16/97. Subsequent air samples were collected on 11/19/97 and 5/1/98.

The manufactured houses differed with respect to size and finish materials (Table 1). Construction techniques and basic materials were identical. The floor assembly was plywood attached to wood joists that were mounted on a steel frame. The exterior and interior walls were framed with wood studs. There were small vented attic spaces. The interior walls and ceilings were covered with gypsum board panels. Many of the wall panels were pre finished with vinyl wallpaper. Floors in the main living areas were carpeted. In House M1, finish floors for the kitchen, baths and utility area were ceramic tile. In the other houses, sheet vinyl was used for these areas. Each house was equipped with a heat pump heating, ventilating and air-conditioning (HVAC) system. House M2 had a ducted fresh air inlet and utilized a fan re-cycling strategy to provide supplemental ventilation (Rudd, 1996). The control device periodically turned on the HVAC system fan to entrain outdoor air if the thermostat did not call for heating and cooling over an extended period (set to 20 min off followed by 10 min on). The other houses had a manually switched exhaust fan mounted in the living area ceiling that was designed for intermittent duty.

Several VOC source substitution treatments were evaluated. Latex paints with VOC contents of 0–1 g L^{-1} were applied in House M2. A carpet system, consisting of a good quality nylon pile carpet and a synthetic fiber carpet cushion, was installed in Houses M2 and M4. These two materials have been shown to have low emissions of VOCs (Schaeffer et al., 1996; Hodgson, 1999). The other houses had conventional latex paint and a lower grade carpet installed over a bonded urethane carpet cushion. All of the houses were decorated and furnished. Decorations variously consisted of painted wainscoting, wallpaper, and built-in cabinetry. The houses were unoccupied, but used as sales models. The HVAC systems were operated on a consistent basis.

The site-built houses were small, detached single-family dwellings designed as entry-level housing (Table 2). They were located in three geographically separate projects. Air samples were collected in House A on 12/10/97 within 1 month of its completion. There were three demonstration houses in Project B that differed primarily with respect to exterior wall construction. Air samples were collected on 4/7/98, about 2 months after completion. Three more demonstration houses in Project C also differed primarily with respect to exterior wall construction. Air samples were collected on 11/4/98, about 1 month after completion. Additional measurements were made the following month in House C3 at typical and reduced ventilation rates.

The site-built houses were all built on cement slab floors. House A was the only two-story structure. The exterior walls were made of various materials. Houses A, B1 and C1 were conventionally framed with wood studs. Houses B2 and B3 had two different types of insulating concrete form walls, consisting of expanded polystyrene sections filled with a concrete core. The exterior walls of House C2 were formed with standard concrete blocks. House C3 was constructed with a lightweight insulating block system. All of the houses had vented attic spaces. The inner walls in all houses were framed with wood studs. The interior wall and ceiling surfaces were painted gypsum board. Finish floors consisted of carpeting and sheet vinyl flooring. A heat pump HVAC system was installed in each house. Houses A and C3 had supplemental ventilation systems; a balanced heat-recovery ventilation (HRV)

Table 1 Specifications for the four manufactured houses

Parameter	Manufactured House I.D.			
	M1	M2	M3	M4
No. bedrooms/bathrooms	2/2	4/2	3/2	3/2
Floor area, m^2	112	169	141	131
Volume, m^3	273	412	344	320
HVAC system	Heat pump	Heat pump	Heat pump	Heat pump
Supplemental ventilation	None[a]	Fan re-cycle[b]	None	None
Carpeted floor area, %	64	76	67	73
Sheet vinyl floor area, %	0	17	21	16
Ceramic tile floor area, %	25	0	0	0
Low-VOC paint, Yes/No	No	Yes	No	No
Low emitting carpet, Yes/No	No	Yes	No	Yes

[a] No supplemental mechanical ventilation other than switched exhaust fan in living area
[b] Ducted outdoor air inlet and automatic fan re-cycle device installed on HVAC system

Table 2 Specifications for the seven site-built houses

Parameter	Site-Built House I.D.						
	Project A	Project B			Project C		
	A	B1	B2	B3	C1	C2	C3
Completion date (mo/yr)	12/97	2/98	2/98	2/98	8/98	8/98	8/98
Sampling date (mo/yr)	12/97	4/98	4/98	4/98	9/98	9/98	9/98
No. floors	2	1	1	1	1	1	1
No. bedrooms/bathrooms	3/1	3/1.5	3/1.5	3/1.5	3/2	3/2	3/2
Floor area, m^2	111	97	92	90	110	110	110
Volume, m^3	272	237	224	220	286	286	286
HVAC system	Heat pump	Heat pump	Heat pump	Heat pump	Heat pump	Heat pump	Heat pump
Supplemental ventilation	HRV[a]	None[b]	None	None	None	None	Fan re-cycle[c]
ASHRAE vent. rate[d], h^{-1}	0.37	0.43	0.46	0.46	0.36	0.36	0.36
Exterior wall type	Frame	Frame	ICF[e]	ICF	Frame	Block	Insul. Block[f]
Carpeted floor area, %	70	80	80	80	84	84	84
Sheet vinyl floor area, %	30	20	20	20	16	12	16

[a] HRV=Balanced heat-recovery ventilation system
[b] No supplemental mechanical ventilation other than switched bathroom exhaust fan
[c] Ducted outdoor air inlet and automatic fan-recycle device installed on HVAC system
[d] ASHRAE Standard 62 recommended ventilation rate for four occupants (ASHRAE, 1989)
[e] ICF=Insulating concrete form of expanded polystyrene with concrete core
[f] Insulated concrete block

system was installed in House A, and a ducted fresh air inlet and a fan re-cycling control were installed in House C3. At the time of sampling, all houses were completely finished, including cabinetry, but they were not furnished or occupied.

Air Sampling and Analysis

Indoor sampling was conducted during periods in which house ventilation rates were relatively constant and at near steady-state conditions. Air samples were collected in the main living area of the houses, typically a combined living/dining room. Sampler inlets were ~1.5 m above the floor. Air samples were also collected at outdoor locations adjacent to the houses. Sample flow rates were regulated with electronic mass-flow controllers.

VOCs were collected on sorbent samplers containing Tenax-TA (P/N 16251; Chrompack, Bergen op Zoom, The Netherlands). Sample flow rates were ~0.1 L min^{-1}. Typical sample volumes were ~1 L. Samples for formaldehyde and acetaldehyde were concurrently collected on silica cartridges impregnated with 2,4-dinitrophenylhydrazine (XPoSure Aldehyde Sampler; Waters Corporation, Milford, MA, USA). Sample flow rates were ~1 L min^{-1}. Sample volumes were ~30 L.

VOCs were quantitatively analyzed by gas chromatography/mass spectrometry (GC/MS) following U.S. Environmental Protection Agency (EPA) Method TO-1 (Winberry et al., 1990). Samples were thermally desorbed with a cryogenic inletting system (Model CP-4020 TCT; Chrompack).

Fifty-two target VOCs were selected for analysis.

These were representative of the major chemical classes of compounds that occur in indoor air, indicative of specific indoor sources, or of interest because they have low odor thresholds or are potent sensory irritants. Many are on the list of 60 target VOCs recommended to be included in an analysis of TVOC (ECA-IAQ, 1997). Multi-point, internal standard calibrations were prepared using pure compounds.

The relative precision of the sampling and analytical method (as measured by a coefficient of variation) has been determined to be about ±10% for many compounds and about ±35% for ethylene and propylene glycols (Hodgson, 1999). The uncertainty in the measurement of acetic acid was greater than ±35%.

The GC/MS method for TVOC has been described (Wallace et al., 1991; Hodgson, 1995). The total-ion current (TIC) chromatogram for a sample was integrated over a retention-time range bounded by n-heptane and n-heptadecane using parameters that captured most of the chromatographic response. The mass of the compounds represented by the sum of the TIC area was calculated relative to the amount and area response of the internal standard. This method was calibrated with a mixture of ten common alkane and aromatic hydrocarbons. The uncertainty in the method when applied across a range of buildings with different VOC sources is estimated to be about ±40% (Wallace et al., 1991).

Aldehyde samplers were analyzed for formaldehyde and acetaldehyde by high-performance liquid chromatography following U.S. EPA Method TO-11 (Winberry et al., 1990).

Measurement of Ventilation Rates

Ventilation rates were measured concurrently with the collection of air samples. HVAC systems were operated during sampling and for at least the prior day to maintain interior temperatures. Supplemental ventilation was used in the three houses with this system. Manually switched exhaust fans were off. Exterior doors and windows were closed. A tracer gas, sulfur hexafluoride (SF_6), was introduced throughout a house by syringe. SF_6 concentrations were measured with a photoacoustic infrared analyzer (Model 1302; Brüel & Kjær Instruments, Naerum, Denmark). After sufficient time for mixing, the ventilation rate in air changes per hour (h^{-1}) was calculated as the slope of the least squares linear regression of the natural log concentration of SF_6 versus time.

Measurement of VOC Emission Rates From Materials

A specimen of plywood flooring (softwood, phenol-formaldehyde resin) was collected from the manufactured house assembly line. Emission rates of VOCs and formaldehyde were determined following the American Society for Testing and Materials Standard Guide D-5116–97 (ASTM, 1997). The specimen was held in a 10.5-L stainless-steel chamber at 23±1° C and 50±10% relative humidity. The exposed surface area was 0.0074 m^2. Nitrogen was introduced at 1.0±0.05 L min^{-1}. Gas samples were periodically collected from the exhaust over 72 h.

Data Analysis

Emission rates of the target compounds were calculated for the houses and the chamber study assuming that the houses and the chamber were ideal continuously-stirred tank reactors (CSTRs) operating at near steady-state conditions. Losses of compounds due to factors other than ventilation (i.e., sink effects) were ignored; consequently, the calculated values were net rates. The steady-state form of the mass-balance model for CSTRs was used (ASTM, 1997). Quasi-steady state, area-specific emission rates (ER) in μg m^{-2} h^{-1} were calculated as:

$$ER = \frac{Va\,(C - C_0)}{A} \qquad (1)$$

Where V is the ventilated volume (m^3); a is the ventilation or air change rate (h^{-1}); C is the air concentration of the compound in the house or chamber (μg m^{-3}); and C_0 is the outdoor air concentration or the chamber inlet air concentration of the compound (μg m^{-3}). For the houses, A is the floor area (m^2), and for the chamber study, A is the exposed surface area of the material (m^2). Normalization by floor area facilitates comparisons among houses of different sizes.

Results

Ventilation Rates

The ventilation rates measured at the time of air sampling are shown in Figure 1. For the manufactured houses, the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) minimum recommended "by volume" rate of 0.35 h^{-1} is applicable (ASHRAE, 1989). The measured rates in the four houses were all in excess of this value. The ventilation rates in Houses A (with an HRV system), C1 and C2 were measurably below the ASHRAE minimum recommended "by occupant" rates (occupancy=1 person per bedroom +1) shown in Table 2.

Concentrations of TVOC and Target Compounds

Table 3 compares the concentrations of 28 target compounds and TVOC in the manufactured and site-built

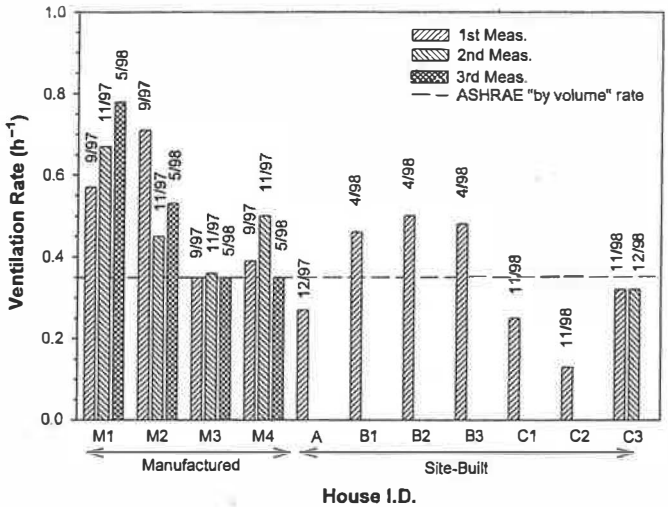

Fig. 1 Ventilation rates measured in study houses at time of air sampling

houses. The target compounds with the highest concentrations were selected for presentation. The GM concentrations for the manufactured houses were calculated using all three sets of data obtained over the study period. The GM concentrations for the site-built houses are for single data sets. In this and subsequent tables, compounds are first ordered by chemical class and then by decreasing volatility within each class. For compounds with concentrations below the lower limit of quantitation, a concentration equal to one-half of the limit was used in the calculation.

The GM concentrations of TVOC in the manufactured and site-built houses were 1.5 and 2.7 mg m^{-3}, respectively. The GSDs for the two house types were similar. The individual house data are shown in Figure 2. Houses C1 and C2 had the highest TVOC concentrations of 4.9 and 3.7 mg m^{-3}, respectively. Outdoor values were typically less than 0.15 mg m^{-3} (GM outdoor concentration=0.09 mg m^{-3} for all data sets).

There was substantial similarity in the concentrations of individual VOCs measured in the two house types. In the manufactured houses, the predominant compounds based on their GM concentrations were α-pinene, ethylene glycol, formaldehyde, acetaldehyde, hexanal, and acetic acid. These compounds were also predominant in the site-built houses. The ranges in their values and in their distributions, as in-

Table 3 Comparison of geometric mean concentrations, standard deviations (GM, GSD) and concentration ranges for 28 selected VOCs (ppb) and TVOC (mg m^{-3}) between four manufactured and seven site-built houses

Compound	Manufactured Houses			Site-Built Houses		
	GM (ppb)	GSD	Range (ppb)	GM (ppb)	GSD	Range (ppb)
n-Decane	2.1	3.4	0.5–16.0	5.5	2.4	2.6–21.9
n-Undecane	1.1	3.3	0.2–7.2	3.6	1.8	2.0–9.1
n-Dodecane	2.7	2.5	0.6–10.5	4.2	1.9	1.2–7.3
n-Tridecane	5.5	3.2	0.8–21.4	5.1	4.5	0.2–15.6
Toluene[a]	2.4	1.6	1.0–5.6	10.3	2.6	3.6–29.2
m/p-Xylene[a]	1.0	1.7	0.5–2.7	3.9	2.3	1.4–11.5
Styrene	0.9	1.7	0.2–2.3	2.6	3.6	0.5–14.3
α-Pinene	16.3	1.8	5.4–35.3	28.1	1.8	12.2–60.0
β-Pinene	4.3	1.9	1.5–10.6	11.5	1.8	5.9–26.3
3-Carene	5.0	2.1	1.3–14.6	3.7	3.0	0.4–9.3
d-Limonene	2.9	1.8	1.1–6.7	5.4	1.9	2.2–12.2
1-Butanol	3.2	1.8	0.6–6.0	12.8	1.8	5.2–21.4
Phenol[a]	2.6	2.0	0.6–5.8	1.4	1.9	0.5–3.6
Ethylene glycol	17.9	2.4	<9.2–43.8	83.0	2.7	20.7–491
Propylene glycol	2.2	2.2	<1.1–12.0	7.6	10.9	<2.2–360
2-Butoxyethanol	2.6	2.0	0.5–5.8	3.1	3.4	0.7–12.3
TMPD-MIB[b]	2.4	1.5	1.4–6.7	9.1	2.2	3.1–25.1
TMPD-DIB[b]	0.8	1.7	0.3–1.9	1.8	5.7	0.1–7.2
Butyl acetate	0.3	2.8	<0.1–2.8	3.2	2.6	0.6–14.1
2-Butanone	6.7	1.9	2.3–28.3	8.8	2.5	2.4–42.1
Formaldehyde[a]	34	1.3	21–47	36	1.6	14–58
Acetaldehyde[a]	10	1.7	3–19	20	1.9	12–57
Hexanal	16.1	1.5	7.9–25.9	26.3	1.6	14.1–51.3
Heptanal	1.5	1.4	0.8–2.5	2.1	1.8	1.3–4.9
Octanal	2.5	1.4	1.4–3.6	2.6	2.0	1.4–7.2
Nonanal	2.8	1.3	1.6–3.9	3.2	2.0	1.0–7.6
Acetic acid[a]	117	2.0	24.9–275	53.9	1.4	36.0–91.8
Hexanoic acid	1.2	2.4	0.3–5.5	1.0	1.7	0.5–2.0
TVOC[a] (mg m^{-3})	1.52	1.4	0.81–2.96	2.72	1.5	1.58–4.88

[a] GM outdoor concentration for all data sets: toluene=1.5 ppb; m/p-xylene=0.5; phenol=0.3 ppb; acetic acid=5.9 ppb; formaldehyde=2 ppb; acetaldehyde=1 ppb; TVOC=0.09 mg m^{-3}

[b] TMPD-MIB=2,2,4-trimethyl-1,3-pentanediol monoisobutyrate; TMPD-DIB=2,2,4-trimethyl-1,3-pentanediol diisobutyrate

dicated by the GSDs, were similar between the two data sets. Additional compounds with relatively high GM concentrations in the site-built houses were toluene, β-pinene, and 1-butanol.

Because of the observed similarities in concentrations between the two house types, the data for the individual compounds were combined into a single set and summary statistics were calculated. The 52 target VOCs plus formaldehyde and acetaldehyde are categorized by their GM concentrations for the 11 houses in Table 4. Eleven VOCs had GM concentrations of <0.5 ppb. Only 10 VOCs had GM concentrations of 5 pbb or higher. Acetic acid had the highest GM concentration of 80 ppb.

Formaldehyde was one of the most abundant compounds (Figure 3). The GM concentration for the entire data set was 40 ppb, with a GSD of 1.6. With the exceptions of Houses C1 and C2, the concentrations were all less than 50 ppb. Formaldehyde concentrations within each manufactured house were relatively constant over time. Outdoor values were 6 ppb, or less (GM outdoor concentration=2 ppb for all data sets).

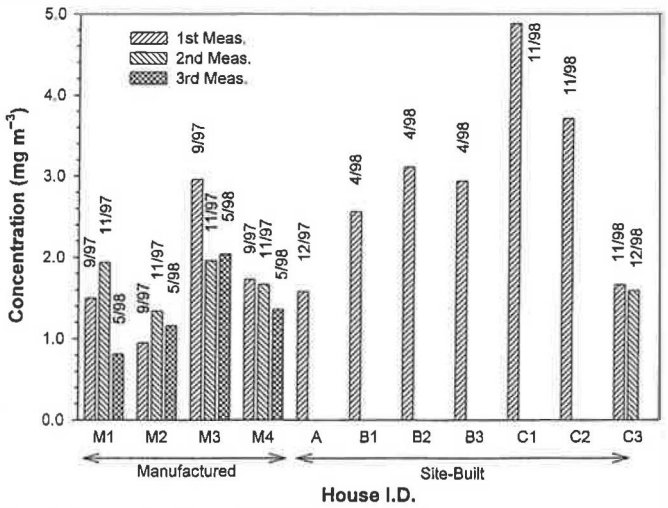

Fig. 2 Concentrations of TVOC in study houses

Emission Rates of TVOC and Target Compounds

Net area-specific emission rates were calculated for the 28 predominant target VOCs and TVOC in the manufactured and site-built houses (Table 5). The GM emis-

Table 4 VOCs categorized by their geometric mean concentrations for the 11 houses

Compound	GM Concentration (ppb)			Chem. Class
	Chem. Class	Compound		
<0.5			1.5–<5.0	
n-Pentadecane*	Alkane HC	n-Decane*		Alkane HC
n-Hexadecane*	Alkane HC	n-Undecane*		Alkane HC
Propylcyclohexane	Cyclic HC	n-Dodecane*		Alkane HC
Butylcyclohexane	Cyclic HC	n-Tetradecane*		Alkane HC
1,3,5-Trimethylbenzene*	Aromatic HC	Toluene*		Aromatic HC
4-Phenylcyclohexene	Aromatic HC	m/p-Xylene*		Aromatic HC
Butylated hydroxytoluene	Alcohol	3-Carene		Terpene HC
Ethyl acetate*	Acetate	d-Limonene*		Terpene HC
4-Methyl-2-pentanone*	Ketone	Phenol		Alcohol
Cyclohexanone	Ketone	Propylene glycol		Glycol ether
Benzothiazole	Misc.	2-Butoxyethanol		Glycol ether
		TMPD-MIB		Ester
0.5–<1.5		Heptanal		Aldehyde
n-Heptane*	Alkane HC	Octanal		Aldehyde
n-Nonane*	Alkane HC	Benzaldehyde		Aldehyde
Methylcyclohexane*	Cyclic HC	Nonanal*		Aldehyde
Benzene*	Aromatic HC			
Ethylbenzene*	Aromatic HC		5.0–<15	
Styrene*	Aromatic HC	n-Tridecane		Alkane HC
1,2,4-Trimethylbenzene*	Aromatic HC	β-Pinene*		Terpene HC
Naphthalene*	Aromatic HC	1-Butanol*		Alcohol
Camphene*	Terpene HC	2-Butanone*		Ketone
2-Ethyl-1-hexanol*	Alcohol	Acetaldehyde		Aldehyde
1-Octanol	Alcohol			
2-(2-Butoxyethoxy)ethanol	Glycol ether		15–<50	
TMPD-DIB	Ester	α-Pinene*		Terpene HC
Butyl acetate*	Acetate	Ethylene glycol		Glycol ether
Acetophenone*	Ketone	Formaldehyde		Aldehyde
2-Furaldehyde	Aldehyde	Hexanal*		Aldehyde
Hexanoic acid	Acid			
			50–<100	
		Acetic acid		Acid

*Included in summary of WAGM concentrations in established dwellings (Brown et al., 1994)

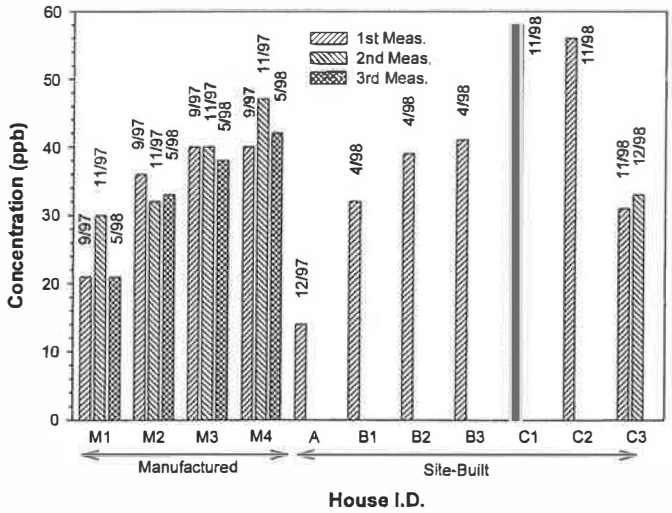

Fig. 3 Concentrations of formaldehyde in study houses

sion rates of TVOC in the manufactured and site-built houses were 1.7 and 2.1 mg m^{-2} h^{-1}, respectively. The GSDs and ranges for the two data sets were similar. There was also substantial similarity in the emission rates of individual VOCs for the two house types. Compounds with GM emission rates greater than 50 μg m^{-2} h^{-1} in the manufactured houses were α-pinene, ethylene glycol, hexanal and acetic acid. These, plus β-pinene and 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate (TMPD-MIB), were also predominant in the site-built houses. Only 11 of the 28 VOCs had GM emission rates that differed by more than a factor of two between the two house types.

Effect of Ventilation Rate

An experiment was conducted in House C3 to measure the effects of a change in ventilation rate on the emission rates of TVOC and individual VOCs. The house was first operated at its typical ventilation rate for one week with samples collected at the end of the week. Then, the house was operated at a lower ventilation rate over the subsequent week by switching off the supplemental ventilation. Again, samples were collected at the end of the week. Ventilation rates measured at the time of sampling of were 0.32 and 0.14 h^{-1}, respectively.

The area-specific emission rates calculated at the two ventilation rates are within ±10% for toluene, 2-butanone, formaldehyde and acetaldehyde, which are the most volatile compounds (Table 6). The emission rates for the less volatile compounds, with the exception of

Table 5 Comparison of geometric mean emission rates, standard deviations (GM, GSD) and ranges of emission rates for 28 selected VOCs (μg m^{-2} h^{-1}) and TVOC (mg m^{-2} h^{-1}) between 4 manufactured and 7 site-built houses

Compound	Manufactured Houses			Site-built Houses		
	GM (μg m^{-2} h^{-1})	GSD	Range (μg m^{-2} h^{-1})	GM (μg m^{-2} h^{-1})	GSD	Range (μg m^{-2} h^{-1})
n-Decane	12.4	4.0	2.1–137	19.8	3.0	2.4–81.8
n-Undecane	7.3	3.9	1.3–75.5	17.8	1.7	7.9–37.7
n-Dodecane	21.8	2.0	7.8–61.9	23.1	2.3	5.3–61.9
n-Tridecane	45.7	2.8	5.1–135	30.3	4.7	1.1–88.8
Toluene	3.9	1.5	<2.7–9.6	25.8	4.0	3.7–117
m/p-Xylene	3.2	1.8	<1.5–9.1	9.5	2.0	<4.1–24.2
Styrene	4.1	1.7	1.8–15.5	8.3	5.1	1.2–71.3
α-Pinene	105	1.7	40.8–189	123	1.7	55.4–227
β-Pinene	27.6	1.7	12.2–51.4	50.6	1.5	27.4–94.9
3-Carene	32.2	1.8	12.2–70.4	16.3	3.2	1.9–58.0
d-Limonene	18.5	1.5	9.9–36.1	23.2	1.7	10.0–44.0
1-Butanol	8.5	1.8	1.8–22.5	23.2	2.3	7.8–59.9
Phenol	9.6	1.9	2.2–16.6	2.1	3.6	0.1–6.0
Ethylene glycol	63.5	2.2	22.0–179	166	3.5	43.6–1.460
Propylene glycol	11.5	2.2	3.0–61.1	18.5	7.7	<7.6–726
2-Butoxyethanol	14.4	2.0	2.7–33.2	12.0	4.8	2.4–72.2
TMPD-MIB	24.3	1.8	10.7–96.4	63.5	2.5	22.5–232
TMPD-DIB	10.8	1.4	7.5–19.4	16.1	5.4	0.5–56.5
Butyl acetate	4.9	3.9	<0.6–22.4	11.6	2.7	2.0–43.3
2-Butanone	21.5	2.1	8.6–90.0	19.1	3.4	5.5–143
Formaldehyde	45	1.3	29–68	31	1.9	10–58
Acetaldehyde	17	1.7	6–46	25	1.6	13–60
Hexanal	76.9	1.4	45.5–137	84.5	1.7	44.0–137
Heptanal	7.7	1.4	3.9–12.9	7.2	1.4	4.9–14.4
Octanal	14.1	1.3	7.4–21.7	10.5	1.6	5.4–23.9
Nonanal	14.7	1.7	3.3–23.3	13.4	1.7	4.3–25.1
Acetic acid	309	2.2	51.9–818	94.8	1.7	32.5–180
Hexanoic acid	1.8	3.1	<0.6–11.2	3.8	2.6	1.2–11.7
TVOC (mg m^{-2} h^{-1})	1.68	1.3	1.08–3.08	2.06	1.8	0.89–3.75

Table 6 Effects of decrease in ventilation rate on emission rates of 24 selected VOCs ($\mu g\ m^{-2}\ h^{-1}$) and TVOC ($mg\ m^{-2}\ h^{-1}$) in House C3

Compound	Chem. Class	Emission rate, $\mu g\ m^{-2}\ h^{-1}$		Ratio Low Vent./ High Vent.
		Week 1 @ $0.32\ h^{-1}$	Week 2 @ $0.14\ h^{-1}$	
n-Decane	Alkane HC	7.8	6.9	0.88
n-Undecane	Alkane HC	6.2	5.1	0.82
n-Dodecane	Alkane HC	11.9	9.2	0.77
n-Tridecane	Alkane HC	50.4	37.2	0.74
n-Tetradecane	Alkane HC	43.1	30.0	0.70
n-Pentadecane	Alkane HC	5.2	3.5	0.67
n-Hexadecane	Alkane HC	10.4	6.3	0.61
Toluene	Aromatic HC	7.8	8.5	1.09
α-Pinene	Terpene HC	56.1	45.8	0.82
β-Pinene	Terpene HC	24.4	19.2	0.79
d-Limonene	Terpene HC	10.9	7.1	0.65
1-Butanol	Alcohol	11.9	11.2	0.94
2-Ethyl-1-hexanol	Alcohol	6.8	4.5	0.66
Phenol	Alcohol	5.2	3.2	0.62
2-Butoxyethanol	Glycol ether	3.6	4.1	1.14
TMPD-MIB	Ester	19.2	11.0	0.57
TMPD-DIB	Ester	69.6	47.6	0.68
2-Butanone	Ketone	6.8	6.7	0.99
Formaldehyde	Aldehyde	29	27	0.93
Acetaldehyde	Aldehyde	16	15	0.94
Hexanal	Aldehyde	42.1	34.0	0.81
Octanal	Aldehyde	8.8	5.9	0.67
Nonanal	Aldehyde	12.6	7.0	0.56
Acetic acid	Acid	246	157	0.64
TVOC ($mg\ m^{-2}\ h^{-1}$)		1.30	0.91	0.70

2-butoxyethanol, decreased by more than 10% at the low ventilation rate. Within the chemical classes of alkane hydrocarbons, terpene hydrocarbons and aldehydes, the ratio of the emission rates at the low and high ventilation rates decreased with decreasing compound volatility.

Temporal Changes in Emission Rates

The manufactured houses were sampled on three occasions approximately 2, 4 and 9.5 months after their completion. Temporal changes in the emission rates of eight individual compounds in these four houses are illustrated in Figure 4a–h. The eight compounds were selected to represent different chemical classes, compound volatility and sources.

Only several compounds in some houses showed a substantial and consistent decrease in emission rate from the first through the third sampling period. n-Decane was emitted at distinctly high rates in House M1 during the first two sampling periods. This was followed by a substantial decrease in the third sampling period. Temporal changes in the emission rates of n-decane in the other houses were relatively small. n-Tridecane was emitted at higher rates than n-decane in Houses M2, M3 and M4. The emission rates of n-tridecane in these houses decreased by less than a factor of two during the study.

The emission rates of α-pinene behaved similarly with time in Houses M1, M2 and M4. There was a distinct increase from the first to the second sampling period followed by a substantial decline in the third sampling period. In both the second and third periods, the emission rates of α-pinene in all of the houses were within narrow ranges.

TMPD-MIB is emitted by conventional latex paints. The data suggest that an unrecorded painting event occurred in House M1 between the first and second sampling periods. The effect was still noticeable in the final sampling period. The data for Houses M2, M3 and M4 show that the emission rates of this compound did not change appreciably during the study.

The emission rates of 2-butanone, one of the most volatile VOCs were elevated in House M2 during the first and second sampling periods. This was followed by a substantial decrease in the final sampling period. In the other houses, the temporal changes in the emission rates of 2-butanone were only about a factor of two or less.

The emission rates of formaldehyde in House M3 were nearly constant with time. Temporal fluctuations in the other three houses were all less than a factor of two. In the final sampling period, formaldehyde emission rates in the four houses were in a range of 37–49 $\mu g\ m^{-2}\ h^{-1}$.

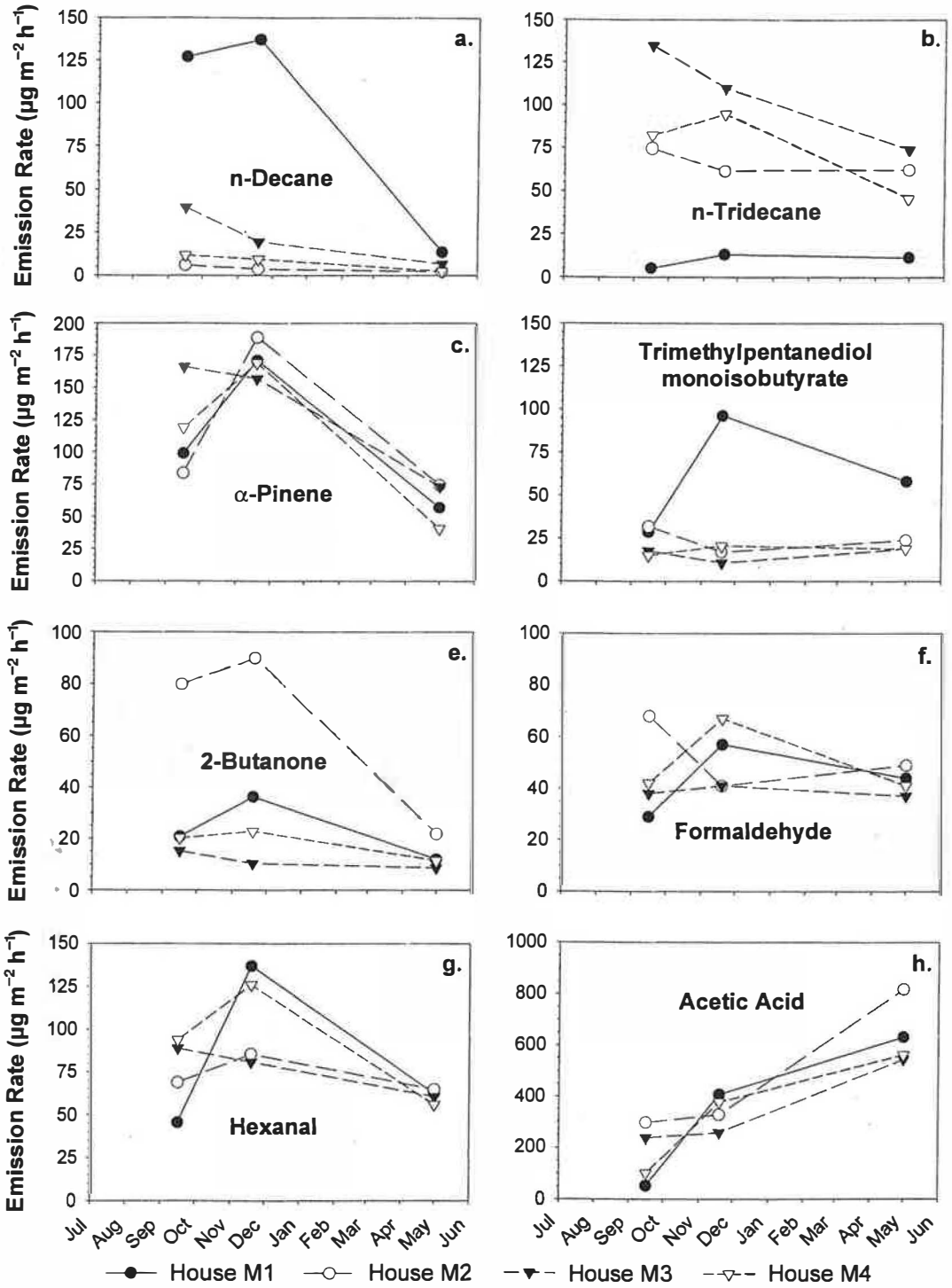

Fig. 4 Emission rates of selected VOCs in manufactured houses

The emission rate of hexanal in House M1 increased substantially from the first to the second sampling period and then declined. A similar, but less pronounced, behavior was observed in House M4. In the other two houses, temporal changes were small. In the final sampling period, hexanal emission rates in the four houses were in a range of 56–65 μg m^{-2} h^{-1}.

In all four houses, the emission rate of acetic acid increased with time from the first through the third sampling period.

Plywood Emissions

The predominant compounds emitted by the plywood specimen were terpene hydrocarbons (α-pinene, β-pinene and d-limonene), formaldehyde, higher molecular-weight aldehydes (hexanal through nonanal), and

Table 7 Emission rates of selected VOCs from plywood specimen

Compound	Emission Rate, $\mu g\ m^{-2}\ h^{-1}$ @ 72 h
α-Pinene	63
β-Pinene	30
d-Limonene	41
Formaldehyde	29
Hexanal	212
Heptanal	11
Octanal	24
Nonanal	22
Acetic acid	340

acetic acid. The area-specific emission rates of these compounds after 72-h exposure in the small chamber are presented in Table 7. α-Pinene, hexanal and acetic acid had the highest rates.

Discussion

TVOC

A recent review concluded that no scientifically valid guidance could be given with respect to indoor TVOC levels (Andersson et al., 1997). There are, however, possible benefits to be derived from keeping exposures to airborne contaminants "As Low As Reasonably Achievable." This ALARA principle suggests that indoor concentrations of VOCs in residences should not exceed levels typically encountered in the housing stock (ECA-IAQ, 1997).

The database of TVOC concentrations in residences is limited, and many of the methods used to quantify TVOC are not directly comparable (Hodgson, 1995). Nevertheless, the reported TVOC concentrations for various indoor environments are frequently about 1 $mg\ m^{-3}$, or lower (Brown et al., 1994). One study of a probability-based sample of 200 existing, occupied houses representing a population of about 600,000 recorded a median TVOC concentration of 0.7 $mg\ m^{-3}$ (Wallace et al., 1991). The TVOC concentrations in the 11 study houses all exceeded this median value for existing occupied houses. There were substantial differences among the study houses presumably due to variations in the emissions of VOCs from material sources. Houses C1 and C2 exceeded the median value by 5–7 times, while House M2 consistently had TVOC concentrations that were within a factor of two of the median value.

Formaldehyde

A survey of formaldehyde concentrations in more than 500 mobile homes (i.e., manufactured houses) of all ages located throughout California was conducted in 1984 and 1985 (Sexton et al., 1986, 1989). The GM concentrations of formaldehyde were 0.072 ppm in the summer and 0.078 ppm in the winter. Maximum concentrations in both seasons exceeded 0.3 ppm. Engineered wood products, such as particleboard and plywood bonded with urea-formaldehyde resin, were recognized to be the primary source of formaldehyde in houses (Meyer, 1979).

More recently formaldehyde concentrations were measured in nine, newly constructed, site built houses in Colorado (Lindstrom et al., 1995). The houses were located in the same geographic area and were of similar size and quality. Prior to occupancy, formaldehyde concentrations were 8–66 $\mu g\ m^{-3}$ (0.007–0.054 ppm) with a GM value of 26 $\mu g\ m^{-3}$ (0.021 ppm). Five months after occupancy, formaldehyde concentrations were 33–81 $\mu g\ m^{-3}$ (0.027–0.066 ppm) with a GM value of 49 $\mu g\ m^{-3}$ (0.040 ppm).

Formaldehyde has well-documented health effects at relatively low concentrations. Residential indoor exposure to formaldehyde can produce symptoms of eye and upper respiratory tract irritation as well as various systemic effects (Gupta et al., 1982; Liu et al., 1991). In addition, the U.S. EPA classifies formaldehyde as a probable human carcinogen (U.S. EPA, 1994). Consequently, guidelines for indoor formaldehyde concentrations have been established at low levels. The World Health Organization (WHO) guideline is 0.082 ppm (WHO, 1987). The California Department of Health Services recommends 0.05 ppm as an "indoor air concentration guideline", and the California Air Resources Board recommends an "action level" of 0.10 ppm with a "target level" of 0.05 ppm or lower (CARB, 1991). The U.S. National Institute of Occupational Safety and Health has set a recommended time-weighted average exposure limit of 0.016 ppm for workplaces because formaldehyde is a probable carcinogen (NIOSH, 1997).

The GM formaldehyde concentration in the four manufactured houses was less than one-half of the historical value for manufactured houses, and all of the values were less than the 0.05 ppm California guideline. The concentrations in the 7 site-built houses were similar with only two values somewhat in excess of 0.050 ppm. The range and GM concentration of formaldehyde in all 11 study houses were similar to the values for the new Colorado houses. The similarity between the manufactured and site-built houses may have been due to the general uniformity in interior construction (i.e., gypsum board panels for walls and ceilings).

Other VOCs

Brown et al. (1994) summarized the literature data for the concentrations of a number of VOCs commonly en-

countered in indoor air. Weighted average GM (WAGM) concentrations (μg m^{-3}) were calculated for 80 compounds detected in established dwellings. Twenty-nine of the compounds were included among the target VOCs for this study (Table 4). The GM concentrations of a number of the 29 compounds in the 11 study houses reported here were near or below the literature WAGM values. Compounds that had notably elevated concentrations in the study houses compared to the literature data for established dwellings included α-pinene, β-pinene, 1-butanol, 2-butanone and hexanal.

Lindstrom et al. (1995) measured concentrations of 2-butanone, acetaldehyde and hexanal in the nine new, site-built houses discussed above. Concentrations of 2-butanone ranged from 4–98 μg m^{-3} (1–33 ppb) over the course of that study. Acetaldehyde concentrations ranged from 5–58 μg m^{-3} (3–32 ppb), and hexanal concentrations ranged from 6–106 μg m^{-3} (2–26 ppb). In the 11 study houses, the ranges in the concentrations of 2-butanone, acetaldehyde and hexanal were 2–42, 3–57 and 8–51 ppb, respectively (Table 3).

Odor and Sensory Irritancy

Many VOCs are known to produce sensory irritancy. However, guidance with respect to exposures to individual VOCs only exists for industrial work environments. Very few studies have been conducted to assess sensory irritancy or other health effects that may result from exposures of the general population to substantially lower concentrations of individual VOCs or mixtures of VOCs.

For some chemical classes of VOCs, odor serves as a warning mechanism. In one study, panels of individuals with and without a normal sense of smell were exposed to homologous series of alcohols and acetates (Cometto-Muñiz and Cain, 1994). The normals detected odors at concentrations about an order of magnitude lower than the concentrations detected as nasal pungency by the anosomics. Therefore, odor thresholds, for which there are substantial data, may serve as general exposure guidelines for some classes of compounds. However, there are caveats that may limit the usefulness of this relationship. For example, adaptation to odors (i.e., odor fatigue) occurs rapidly while there may be no adaptation or even a temporal increase in response to sensory irritants. Also, the cumulative effects of exposures to complex mixtures of compounds may differ for odor and sensory irritation responses.

A number of commonly occurring alcohols, aldehydes and carboxylic acids produce objectionable odors at relatively low concentrations. In Table 8, the

Table 8 Maximum concentrations of 23 selected VOCs in four manufactured and seven site-built houses compared to odor thresholds, mouse irritancy thresholds ($0.03 \times RD_{50}$) and threshold limit values (TLVs)

Compound	Manuf. Max (ppb)	Site-blt. Max (ppb)	Odor Thres.[a] (ppb)	0.03 x RD_{50}[b] (ppb)	Rel. Irritancy[c]	TLV[d] (ppb)	1/40TLV[e] (ppb)
n-Decane	16.0	21.9	741	na[f]	na	na	na
n-Undecane	7.2	9.1	1,170	na	na	na	na
n-Dodecane	10.5	7.3	2,040	na	na	na	na
n-Tridecane	21.4	15.6	2,140	na	na	na	na
Toluene	5.6	29.2	1,550	136,000	1.0	50,000	1,250
m/p-Xylene	2.7	11.5	398	40,000	3.4	100,000	2,500
Styrene	2.3	14.3	145	17,000	7.9	50,000	1,250
α-Pinene	35.3	60.0	692	na	na	na	na
d-Limonene	6.7	12.2	437	na	na	na	na
1-Butanol	6.0	21.4	490	131,000	1.0	50,000	1,250
Phenol	5.8	3.6	110	5,000	27	5,000	125
2-Butoxyethanol	5.8	12.3	339	85,000	1.6	25,000	625
TMPD-MIB	6.7	25.1	78	na	na	na	na
Butyl acetate	1.5	14.1	195	22,000	6.2	15,000	375
2-Butanone	28.3	42.1	7,760	513,000	0.3	200,000	5,000
Formaldehyde	47	58	1,150	300	440	300	8
Acetaldehyde	19	57	186	103,000	1.3	25,000	625
Hexanal	25.9	51.3	13.8	34,000	4.0	na	na
Heptanal	2.5	4.9	4.8	na	na	na	na
Octanal	3.6	7.2	1.4	na	na	na	na
Nonanal	3.9	7.6	2.2	na	na	na	na
Acetic acid	275	91.8	145	11,000	12	10,000	250
Hexanoic acid	5.5	2.0	12.6	na	na	na	na

[a] Odor thresholds are from Devos et al. (1990), except TMPD-MIB (Wolkoff and Nielsen, 1993)
[b] Mouse RD_{50} values are from Schaper (1993)
[c] Relative irritancy was calculated using toluene as reference (VOC RD_{50}/Toluene RD_{50})
[d] 8-h Time-weighted average Threshold Limit Values (ACGIH, 1993)
[e] TLVs were adjusted following the procedure of Nielsen et al. (1997)
[f] na=Not available

maximum concentrations of 23 individual compounds measured in the manufactured and site-built houses are compared to their odor thresholds (Devos et al., 1990; Wolkoff and Nielsen, 1993). There are large standard errors associated with these thresholds because of methodological differences and the wide variability in human response (Amoore and Hautala, 1983). The maximum concentrations of hexanal, heptanal, octanal, nonanal, and acetic acid in both house types approached or exceeded their respective odor thresholds. Additionally, all concentrations of hexanal and octanal in the 11 houses were either near or exceeded the thresholds. Maximum concentrations of TMPD-MIB and acetaldehyde in the site built houses and of hexanoic acid in the manufactured houses were within a factor of five of their odor thresholds.

While human data on sensory irritancy, or pungency for VOCs are limited, considerably more data have been obtained using a mouse bioassay (ASTM, 1984). This bioassay determines a RD_{50}, the concentration of an airborne irritant that is calculated to produce a 50% decrease in the respiratory rate of exposed mice. Generally, RD_{50} concentrations correlate well with Threshold Limit Values (TLVs) for occupational exposures that are based on sensory irritation (Alaire, 1981; ACGIH, 1993; Schaper, 1993). Multiplying the RD_{50} values by a factor of 0.03 puts them on a similar concentration basis as TLVs (Alaire, 1981). Mouse RD_{50} values are available for 12 of the target compounds (Schaper, 1993). These values were multiplied by 0.03, and the resulting concentrations are listed in Table 8. Relative irritancies, which were calculated by normalizing the RD_{50} values for individual VOCs to the RD_{50} for toluene, are also listed.

The relative irritancies show that formaldehyde is by far the most likely of the twelve compounds to produce sensory irritation effects. Phenol and acetic acid are also relatively potent irritants compared to the other compounds. Acetic acid is potentially the more significant irritant because it occurred at relatively high concentrations.

TLVs for occupational exposures are available for 11 of the compounds in Table 8. Nielsen et al. (1997) proposed using occupational exposure limits as a basis for indoor air concentration guidelines. They suggested adjusting occupational limits be a factor of 40 to account for the different exposure periods (40 h per week for an industrial worker versus 168 per week for a full-time residential occupant) and to provide a safety factor of ten for more sensitive populations. Thus, the TLVs for the 11 compounds were multiplied by a factor of 0.025 (1/40) according to this procedure (Table 8). Comparison of concentrations measured in the manufactured and site-built houses with the proposed TLV-based limits shows that formaldehyde concentrations consistently exceeded the limit and acetic acid concentrations approached and occasionally exceeded the limit.

Sources of VOCs

Table 9 lists VOCs emitted by latex paints and carpet and sheet vinyl flooring materials (Hodgson, 1999). Many conventional latex wall paints contain ethylene glycol and/or propylene glycol as solvents and TMPD-MIB as a coalescing aid. The emissions of glycol ethers and TMPD-MIB from latex paints applied to gypsum wall board can persist at elevated levels for a number of months (Chang et al., 1997; Hodgson, 1999). Sheet vinyl flooring is a source of many compounds including n-decane, n-tridecane, toluene, 1,2,4-trimethylbenzene, phenol and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TMPD-DIB). Generally, the emissions of the less volatile components, such as phenol and TMPD-DIB, persist for months (Hodgson, 1999).

The similarities in the types of VOCs and in VOC concentrations indicated that indoor air quality in the study houses was impacted by the same or similar sources of VOCs. The impact of latex paint was indicated by the presence of ethylene glycol, propylene glycol and TMPD-MIB. The predominant source of phenol and TMPD-DIB was likely sheet vinyl flooring. A portion of the normal alkane hydrocarbons, such as n-decane, n-tridecane and n-tetradecane, also probably originated from sheet vinyl flooring, although there may have been other sources. Wood and engineered wood products emit terpene hydro-

Table 9 Indoor sources of selected VOCs based on emission studies of latex paints and carpet and vinyl flooring materials (Hodgson, 1999)

Compound	Identified Source
n-Decane	Sheet vinyl flooring
n-Dodecane	Sheet vinyl flooring
n-Tridecane	Sheet vinyl flooring
n-Tetradecane	Sheet vinyl flooring
Toluene	Sheet flooring adhesive
Styrene	Carpet with SBR* latex
1,2,4-Trimethylbenzene	Sheet vinyl flooring
4-Phenylcyclohexene	Carpet with SBR latex
Phenol	Sheet vinyl flooring
Butylated hydroxytoluene	Bonded urethane carpet cushion
Ethylene glycol	Latex paint
Propylene glycol	Latex paint
2-(2-Butoxyethoxy)ethanol	Latex paint
TMPD-MIB	Latex paint
TMPD-DIB	Sheet vinyl flooring
Cyclohexanone	Sheet vinyl seam sealer
Benzothiazole	Rubber cove base

*SBR=Styrene-butadiene-rubber

carbons. The composition of the terpene hydrocarbons is determined by the species of wood (Baumann et al., 1999). The chamber results showed that the plywood used for the floor in the manufactured houses was a source of α-pinene, β-pinene and d-limonene, but not a source of 3-carene. Approximately 70% of the floor area in the houses was carpeted. It is assumed that VOCs emitted by plywood diffuse through carpet cushion and carpet. If so, the plywood floor may have been an important source of many, but probably not all of the terpene hydrocarbons detected in the manufactured houses. Engineered wood products emit formaldehyde, hexanal and other aldehydes including heptanal, octanal and nonanal (Baumann et al., 1999). The engineered wood products with exposed indoor surfaces included the floor (manufactured houses and the two-story site-built house) and the cabinetry components (particleboard, medium-density fiberboard and hardboard). The results of a study to characterize the emissions of VOCs from the predominant wood and engineered wood products used in the construction of the manufactured houses will be subsequently reported.

The source of the acetic acid in the study houses is less certain. Concentrations were elevated in all of the houses. In the manufactured houses, the emission rate of acetic acid increased with time. The source had to be a material used in large quantity since the mass emission by the end of the study was estimated to be in the range of 2–3 g per day. Plywood is one likely source based on the chamber results. However, another source(s) may have contributed.

The use of low VOC content paints and the installation of a low-emitting carpet system were attempted as source substitution treatments in the manufactured houses. Although not part of the study design, ceramic tile was substituted for sheet vinyl in one house. The impacts of these source substitutions proved difficult to evaluate. One unanticipated problem was the lack of control over the houses after they left the manufacturing facility. This meant that conventional latex paints were probably used to decorate the house that was originally painted with the low VOC products. Another factor was that contemporary carpet assemblies have low VOC emissions relative to many other indoor sources. Consequently, differences in the emission rates of carpet-related compounds between treated and non-treated houses were negligible. The only notably lower VOC emission rates that could be attributed to source substitution occurred in the house without sheet vinyl. In this house, the emission rates of n-tridecane, n-tetradecane and phenol were distinctly lower than in the other three houses.

Conclusions

The predominant compounds detected in the new manufactured and site-built houses were generally the same. In addition, the concentrations of many of the target compounds were similar in the two types of houses. The similarities between the manufactured and site-built houses were presumably due to the use of generally comparable construction practices and materials. It was notable that the concentrations and emission rates of formaldehyde in the manufactured houses were considerably less than historically reported values, and that they were similar to the concentrations and emission rates in the site-built houses.

Odor was not directly assessed. However, the data suggest that many individuals would be able to detect objectionable odors in the houses due primarily to consistently elevated concentrations of higher molecular-weight aldehydes and acetic acid. Such odors may persist for months. Objectionable odors are a nuisance, which may impact occupant behavior and house energy consumption. For example, occupants may tend to open windows and exterior doors for more ventilation even during heating or cooling periods.

Formaldehyde concentrations in the study houses were typically near or below 0.05 ppm, a level widely regarded as acceptable for residences. Nevertheless, formaldehyde is a potent irritant that may produce sensory irritation in some individuals even at low levels. Acetic acid, a relatively potent irritant present at elevated concentrations in some houses in this study, may be a contributor to sensory irritation.

Three of the seven site-built houses had ventilation rates below the ASHRAE minimum recommended value at the time of sampling. Increasing the ventilation rate in these houses to meet the ASHRAE value would be expected to reduce VOC concentrations.

The study demonstrated that emission rates did not decrease rapidly with time for compounds that are of interest because of their potential odor or irritation effects. For example, the emission rates of formaldehyde and hexanal were generally similar at the beginning and end of the 7.5-month study period in the manufactured houses. The emission rate of acetic acid substantially increased over this period.

Source reduction through substitution of materials or modification of building practices is generally the preferred method for reducing occupants' exposures to VOCs. Increased ventilation in excess of the ASHRAE recommendation is a less desirable solution because it can increase energy consumption. Consequently, a continued effort should be made to identify and reduce the sources of objectionable VOCs in the construction and finishing of new houses. Practices such as the use

of low VOC content paints and low-emitting carpet systems should be continued. Source substitution treatments should be attempted for other materials such as engineered wood products. High priority should be given to identifying the sources of acetic acid.

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