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ABSTRACT

The concentrations of formaldehyde, 52 individual volatile organic compounds (VOCs) and total VOCs (TVOC) were measured in four new manufactured houses on three occasions over a period of approximately nine months following completion of their construction. The houses were furnished, but unoccupied, model homes produced by a single U.S. manufacturer. Several of the houses incorporated interior finish materials with lower VOC emissions than standard materials. One house had a modified ventilation system. Ventilation rates were measured concurrently with the collection of air samples. A steady-state mass-balance model was used to calculate the area-specific emission rates of the target compounds and TVOC. The emissions of formaldehyde and VOCs from a specimen of plywood used as the floor sheeting were additionally quantified.

The median formaldehyde concentration in the four houses was 37 parts-per-billion (ppb). The formaldehyde concentrations were all less than the most restrictive guideline for this compound of 50 ppb. The concentrations of many of the target VOCs were low. Thirty-one of the VOCs had median concentrations that were at or below 1 ppb. Seven of the compounds were among the most abundant VOCs in all four houses. These compounds were alpha-pinene, beta-pinene, 3-carene, ethylene glycol, hexanal, 2-butanone, and acetic acid. The concentrations of the aldehydes, hexanal, octanal and nonanal, in the four houses were either near or exceeded their respective odor thresholds. The concentrations of acetic acid increased with time. In the final sampling period, the odor threshold for acetic acid was exceeded in all of the houses. The range of TVOC concentrations in the four houses was 0.8 to 3 mg m^{-3}, with a median value of 1.6 mg m^{-3}. These concentrations were somewhat lower than TVOC concentrations previously measured in several new site-built houses, and the median concentration was only about twice the typical value for existing residences. The house with the modified ventilation system and several lower emitting materials had consistently low TVOC concentrations that were near 1 mg m^{-3}.

There were no large decreases with time in the emission rates of the individual VOCs or TVOC during the course of the study. However, the emission rates were often lowest in the final sampling with the notable exception of the acetic acid emission rate that increased with time. The source of the aldehydes was most likely engineered wood products, such as the plywood floor sheeting and possibly other structural or interior components. The source of the acetic acid was uncertain. The effects of the source substitution treatments were measurable but turned out to be relatively minor due to the predominance of other sources.

INTRODUCTION

Background

Indoor sources of volatile organic compounds (VOCs) and other gaseous contaminants are a primary determinant of indoor air quality in houses. Many of the materials that are used to construct and to finish the interiors of new houses emit VOCs. Some of these materials also emit formaldehyde. The emissions of VOCs and formaldehyde from materials can result in substantial contamination of indoor air. It is recognized that such contamination is most likely a cause of acute health effects and discomfort among building occupants (Andersson *et al.*, 1997). Consequently, methods are being developed to assess the potential for the emissions of VOCs from building materials to produce sensory irritation or objectionable odors (Wolkoff *et al.*, 1991; Wolkoff and Neilsen, 1996; Maroni and Lundgren, 1998).

In the past, formaldehyde concentrations in excess of 0.1 ppm were frequently encountered in manufactured houses (NRC, 1981; Sexton *et al.*, 1986 and 1989). The elevated concentrations were due to the emissions of formaldehyde from engineered wood products. An understanding of the problem lead to the development of test methods and the establishment of guidelines for the emissions of formaldehyde from wood products by the U.S. Department of Housing and Urban Development (HUD, 1984). Today, the emissions of formaldehyde from wood products are substantially lower (Kelly, 1996). Construction materials and methods for manufactured houses have also changed considerably. Consequently, it is likely that the indoor concentrations of formaldehyde in manufactured houses have been significantly reduced relative to historical values. On the other hand, a variety of new or reformulated products and materials are used in the construction of new houses including manufactured houses, with generally unknown impacts on VOC concentrations and occupant exposures.

Building ventilation is also a main determinant of indoor air quality in houses. Ventilation serves as the primary mechanism for the removal of gaseous contaminants generated indoors. Therefore, higher contaminant concentrations are expected at lower ventilation rates given constant emission source strengths. The current trend in new house construction, which is supported by various government energy conservation programs, is to make building envelopes tighter. This practice improves energy efficiency by decreasing the infiltration of unconditioned outdoor air. Consequently, ventilation rates in new houses can be relatively low with a related potential for degraded indoor air quality.

It is likely that acceptably low indoor VOC concentrations can be achieved in new, tightly constructed, houses by the selection of building and interior finish materials with relatively low VOC impacts. It may also be possible to treat some existing materials to reduce their emissions of VOCs. Implementation of such source substitution or reduction techniques may result in improved marketability of new houses, increased occupant health and comfort, and reduced energy costs due to the possibility of lower ventilation requirements.

Study Objectives

There is a general lack of data on the sources and concentrations of VOCs in both site-built and manufactured new houses in the United States. This study was designed to collect some of these data for new manufactured houses.

The primary objectives of the study were to: 1) quantify the airborne concentrations of total VOCs, selected individual VOCs, and formaldehyde in four new manufactured houses over a period of approximately nine months following completion of their construction; 2) compare the concentrations of total and individual VOCs to values typically measured in buildings; 3) compare the concentrations of formaldehyde to air quality guidelines; 4) compare the concentrations of selected VOCs to their respective odor thresholds; and 5) document the temporal changes in the emission rates of the quantified constituents over the study period. Secondarily, the study attempted to: 1) identify the sources of specific VOCs; and 2) evaluate the effectiveness of several source substitution treatments for reducing the emission rates and concentrations of VOCs.

Overview of the Study Plan

The study was conducted at the Palm Harbor Homes Inc. Model Center in Plant City, FL. The Model Center is sited adjacent to a Palm Harbor Homes, Inc. manufacturing facility. Each year, new model houses are produced by the factory for display at the Model Center. A preliminary investigation was conducted in April 1997 to identify the VOCs in indoor air in two 1997-model houses that were approximately nine months old and to measure the concentrations of total VOCs, individual VOCs and formaldehyde in these houses. The preliminary field results were used in conjunction with literature data and the early results of an on-going laboratory-based study of common indoor sources of VOCs (Hodgson, 1998) as the basis for suggestions regarding the substitution of several sources of VOCs used in the houses. These suggestions were limited to materials for which there were readily available commercial alternatives with likely lower emission rates of VOCs.

The 1998-model houses were produced and set up at the Model Center during July and August 1997. The study was conducted using four of these new houses. Source substitutions were made in several of the houses either during the manufacturing or set up phases. The heating, ventilating and air conditioning (HVAC) system in one of the houses with substituted sources was modified for another component of the study. All of the houses were decorated and fully furnished, but unoccupied. Air samples for the analysis of VOCs and formaldehyde were collected beginning in September 1997. Air samples were subsequently collected in November 1997 and May 1998. On each occasion, the samples were collected at a central location in each house and at a nearby outdoor location. The air change rate in each house was simultaneously measured by a tracer-gas decay method.

The samples were analyzed by high-performance liquid chromatography (HPLC) for formaldehyde and by gas chromatography/mass spectrometry (GC/MS) for total VOCs (TVOC) and a target list of 60 individual target VOCs. The most abundant compounds in the houses were identified. The concentrations of the target analytes were compared among the four houses and as a function of time. The concentrations of selected compounds were additionally compared to concentrations typically measured in buildings, published odor thresholds and any relevant concentration guidelines. The indoor and outdoor concentration data, the ventilation rates and the house parameters were used in a mass-balance model to calculate the area-specific emission rates of the target analytes. The use of specific emission rates facilitated the comparison of source characteristics among the houses and with time.

A specimen of plywood floor sheeting was collected at the manufacturing facility and tested for the emissions of formaldehyde and other VOCs using a small-scale environmental chamber. The measured emission rates of these compounds were compared to the respective emission rates calculated for the houses. The emission rates of selected VOCs in the houses with substituted materials were compared to the respective emission rates in the houses without these modifications to evaluate the effectiveness of the source substitution procedures.

METHODS

Description of the Study Houses

All of the houses employed in this study were produced by Palm Harbor Homes, Inc. at their manufacturing facility in Plant City, FL. Within three weeks of production, the study houses were moved from the factory and set up at the adjacent Palm Harbor Homes, Inc. Model Center where they were professionally decorated and fully furnished. The houses were unoccupied and used solely for sales purposes. They were open to visitors six days a week. The HVAC system in each house was operated during regular visitor hours by a thermostat.

In April 1997, a preliminary investigation was conducted in two 1997-model houses that were approximately nine months old at that time. These houses are identified as PH13-Pre and PH18-Pre. The floor areas were 177 and 146 m^2, respectively. The ceiling height was 2.4 m. The subfloors were plywood sheeting. The floors were covered with a combination of carpet and sheet vinyl flooring. Interior finish details were not recorded.

The four 1998-model houses used in the study were produced and set up at the Model Center during July and August 1997. The specifications for the houses, identified as PH2, PH18, PH19 and PH20, are given in Table 1. All of the houses had plywood floor sheeting. The floor areas ranged from 112 to 169 m^2. The ceiling height was 2.4 m. A central occupant-controlled exhaust fan was installed in each house to comply with HUD ventilation requirements. The HVAC system in House PH18 was modified for the energy performance component of the study (to be separately reported). The ductwork in House PH18 incorporated a fresh air inlet that entrained outdoor air into the return duct whenever the system fan was operating. An automatic fan re-cycle device was additionally installed to periodically turn on the system fan if the thermostat did not call for heating and cooling over an extended period. The control parameters for the device were user programmable and were set at 20 minutes off followed by 10 minutes on for the purpose of this study.

The types and amounts of the predominant interior finish materials varied among the four houses. All of the houses were carpeted. The carpet assembly installed Houses PH2 and PH19 consisted of a bonded urethane carpet cushion and a standard grade carpet. The carpet assembly installed in Houses PH18 and PH20 consisted of a synthetic fiber carpet cushion and a better grade Nylon fiber carpet. These substituted materials were expected to have generally lower emission rates of VOCs than the bonded urethane cushion and the standard grade carpet based on laboratory chamber studies of similar materials (Hodgson, 1998; Schaeffer *et al.*, 1996). House PH2 differed from the others in that it utilized ceramic tile on the kitchen and bathroom floors and did not contain any sheet vinyl flooring. All of the other houses utilized sheet vinyl flooring on the kitchen, bathroom and utility room floors. There were three different wall finishes used in various combinations in the houses. House PH2 had pre-finished, vinyl covered, gypsum wallboard in the kitchen and bathrooms. The walls in all of the other rooms were painted textured gypsum wallboard. Houses PH18, PH19 and PH20 had painted textured gypsum wallboard in the living, dining and family rooms only. Vinyl covered wallboard was used in all of the other rooms including the bedrooms. Houses PH18, PH19 and PH20 had painted wainscoting in the living room. House PH19 also had painted wainscoting in the dining room. The textured gypsum wallboard in Houses PH18, PH19 and PH20 was painted with a new generation, low-VOC, latex paint. It is not known what type of paint was used on the wainscoting. House PH2 was painted with a conventional latex paint.

Air sampling for the investigation of the four study houses was initially conducted on September 16, 1997. Subsequent air samples were collected on November 19, 1997 and May 1, 1998.

Sampling and Analysis of VOCs

An attempt was made to conduct indoor air sampling during periods in which the house ventilation rates were constant and near steady-state conditions. The indoor air samples were collected in the main living areas of the houses, which typically were the combined living and dining rooms. The air samplers were attached to a tripod so that their inlets were approximately

1.5 m above the floor. Duplicate samples were collected for VOCs and a single sample was collected for formaldehyde in each house on each sampling occasion. Sampling was similarly conducted on each occasion at a single outdoor location that was adjacent to one of the houses.

Air samples for the analysis of individual VOCs and TVOC were collected on sorbent samplers which contained Tenax®-TA (Part No. 16251, Chrompack, The Netherlands). The air sample flow rates were about 0.1 L min-1. These rates were regulated with electronic mass flow controllers. Sample volumes were varied depending upon the expected analyte concentrations and were typically were about 1 L. The sorbent samplers were cleaned and conditioned prior to use by heating them in a helium gas stream to 300° C for 30 minutes.

The GC/MS method used for the analysis of VOCs collected on sorbent samplers is a modification of U.S. Environmental Protection Agency (EPA) Method TO-1 (Winberry *et al.*, 1988a). The sample components were thermally desorbed from a sampler using a cryogenic inletting system (Model CP-4020 TCT, Chrompack, The Netherlands). The sample components were introduced into a capillary gas chromatograph (GC) equipped with liquid nitrogen sub-ambient cooling (Model 5980 Series II, Hewlett-Packard Corp.). The GC was connected via a direct capillary interface to an electron-impact quadrupole mass spectrometer (Model 5970B, Hewlett-Packard, Corp.). The mass spectrometer was operated in the scan mode. The specifications for this system are given in Table 2.

An internal standard (ISTD) was added to all samplers, including standards, immediately prior to their analysis. The ISTD was 120 ng of bromofluorobenzene. This was generated by a gravimetrically calibrated diffusion source and was transferred to the samplers with a gas-tight syringe.

For qualitative analysis, the spectra of the peaks in the total-ion-current (TIC) chromatograms were first compared to spectra contained in a database of commonly occurring VOCs created in the laboratory from analyses of pure compounds. These analyses were conducted with the same methods used for the analysis of the samples. If a spectrum of a compound matched a spectrum of a compound in the database and if the compounds' retention times also matched, then the identification was "confirmed." If no match was obtained, then the unknown spectrum was compared to the spectra contained in the electronic NIST/EPA/NIH Mass Spectral Data Base of approximately 75,000 entries (Heller and Milne, 1978). The analyst decided whether an identification was "probable" based on the match quality and the reasonableness of the retention time. Less certain matches were described as "tentative." In some cases, no strong match was obtained, and the compound was "unidentified."

Sixty target VOCs were selected for quantitative analysis. The selection of these compounds was based on a variety of criteria. The target compounds are representative of the major chemical classes of compounds that occur in indoor air. All of the compounds have been detected in indoor air quality investigations, and many of them are often present at relatively high abundance. Some of the compounds are indicative of specific indoor sources. Some of the compounds are important as contaminants because they have relatively low odor thresholds or they are sensory irritants. Other compounds have been classified as toxic air contaminants by the U.S. EPA. Thirty-two of the compounds are among the 56 target VOCs for the U.S. EPA BASE Study of office buildings (Girman *et al.*, 1995). Forty-five of the compounds are among the 60 target VOCs recommended by European researchers to be included in an analysis of TVOC (ECA-IAQ, 1997).

For quantitative analysis, abundant and characteristic mass ions for the compounds of interest were extracted from the TIC chromatograms and integrated by the data system. Mass responses were determined using multi-point ISTD calibrations.

For compounds with high to intermediate volatility, standard gas mixtures were created by injecting a several microliter aliquot of a liquid mixture of the compounds into a 2-L flask with a septum cap which was then heated and maintained at 65° C (Riggan, 1984). A sample was withdrawn from the flask with a gas-tight syringe and injected into a helium gas stream flowing through a clean sampler. Calibrations were prepared by analyzing a range of volumes of the gas mixture.

For compounds with lower vapor pressures, dilute liquid standards were prepared in a low-boiling solvent such as methanol or n-pentane, and microliter amounts of the standard were injected directly onto a sampler. The sampler was purged with helium to remove most of the solvent and then analyzed following the normal procedure. Calibrations were prepared by analyzing different volumes or serial dilutions of the liquid standard.

The GC/MS TIC method used for the analysis of TVOC has previously been described (Wallace *et al.*, 1991; Hodgson, 1995). The TIC chromatogram for a sample was integrated over a broad retention-time range bounded by the retention times of n-hexane and n-heptadecane. The integration parameters that were used captured almost all of the chromatographic area within this range. The integrated areas minus the area of the ISTD were summed. The mass of the compounds represented by the sum were calculated relative to the known amount of the ISTD. This calculation used an average relative TIC response factor determined for ten commonly occurring normal alkane and aromatic hydrocarbons. These compounds were: n-heptane, n-octane, n-nonane, n-undecane, n-tridecane, benzene, toluene, ethylbenzene, m-xylene, and 1,2,4-trimethylbenzene. Because of the variation in the relative TIC response of different classes of compounds, the uncertainty in the method when applied across a range of buildings with different sources of VOCs is estimated to be approximately ±40 percent (Wallace *et al.*, 1991).

Sampling and Analysis of Formaldehyde

Air samples for the analysis of formaldehyde were collected on silica cartridges impregnated with an acid solution of 2,4-dinitrophenylhydrazine (XPoSure Aldehyde Sampler, Waters Corp.). As an air sample is pulled through a tube, the reagent reacts with carbonyl compounds to form stable derivatives that are retained by the tube. The air sample flow rate was about 1 L min^{-1}. This flow rate was regulated with an electronic mass flow controller. The sample volume was typically about 30 L.

For analysis, a sampling cartridge was eluted with 2 mL of acetonitrile. Sample extracts were analyzed for the formaldehyde derivative using by HPLC generally following U.S. EPA Method TO-11 (Winberry *et al.*, 1988b). The compound was separated on a microbore, reverse-phase C_{18} column (Symmetry C18, Part No. WATO56975, Waters Corp.) with a gradient mixture of water and acetonitrile as the mobile phase. The HPLC instrument (Model 1090 LC, Hewlett-Packard Corp.) was equipped with a dual-pump solvent delivery system and a diode-array UV detector. The absorbance of the derivative was measured at 360 nm. Five-point external calibrations were prepared periodically during the study from standard solutions of the formaldehyde derivative. The lower limit of quantitation for formaldehyde in a 30-L sample was approximately 2 µg m^{-3}.

Measurement of Ventilation Rates

Ventilation rates were measured in the study houses concurrently with the collection of the air samples. Sulfur hexafluoride (SF_6) was used as the tracer gas. The SF_6 concentrations were determined with a photoacoustic infrared analyzer (Model 1302, B&K Instruments, UK). The analyzer was located in the main living area of a house near the air samplers. After the air sampling equipment had been set up but prior to the collection of the air samples, a small volume of pure SF_6 was injected into the HVAC return duct or directly into the interior of the house. The concentration of SF_6 in the main living area was monitored at approximately one-minute intervals. After the SF_6 concentration stabilized and began to decay, the collection of the air samples was initiated. The monitoring of the decay of the SF_6 concentration continued throughout the sample collection period. 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 in hours.

Measurement of VOC Emission Rates From Materials

A scrap piece of 2-cm thick plywood used as floor sheeting was collected from the assembly line at the manufacturing facility in April 1997. The emission rates of VOCs and formaldehyde from this plywood specimen were determined using a small-scale environmental chamber facility. The chamber facility and the individual chambers were constructed and operated following the American Society for Testing and Materials Standard Guide D-5116-97

(ASTM, 1997). The specifications and operating parameters for the small-scale chambers are summarized in Table 3. The chambers consisted of polished 316 stainless steel, cylindrical vessels. The chambers were equipped with stainless-steel lined lids that were sealed with Teflon-coated silicone gaskets. The internal volume of the chambers was 10.5 L. The chambers were held at 23 ± 1° C in an incubator.

The inlet gas for a chamber was high-purity nitrogen supplied by gas cylinders. The flow rate of nitrogen was regulated at 1.0 ± 0.05 L min^{-1} with a mechanical flow controller and was measured with an electronic mass-flow sensor. The gas stream was split into two streams with balanced flow rates. One of these passed through a bubbler containing distilled water held in the incubator. This stream was mixed with the dry gas stream to generate an inlet gas stream with 50 ± 10 percent relative humidity at 23° C. The humidified gas stream was introduced into the chamber through a fitting on the lid with a tubing extension that terminated near the bottom of the chamber. Gas exited the chamber through another fitting on the lid. A sampling manifold constructed of stainless-steel tube fittings was attached to the outlet of this fitting. A combined temperature and humidity probe (Part No. HMD 30 YB, Vaisala, Finland) was inserted into the chamber through a third fitting. Chamber temperature, relative humidity and inlet gas flow rate were monitored and recorded throughout an experiment at five-minute intervals with a PC-based data system.

A clean, empty chamber was operated at the temperature, humidity and ventilation conditions of the experiment for one hour. The plywood was cut to size and then sealed into a stainless-steel holder that covered one side and the freshly cut edges of the specimen. The exposed surface area of the specimen was 0.0074 m^2. The chamber was opened, and the specimen was placed on a metal rack that held the specimen near the approximate center of the chamber. The chamber lid was quickly re attached and the data system was re started. This established the initial time point for the experiment. Samples for VOCs and aldehydes were simultaneously collected from the sampling manifold at average elapsed times of 24, 48 and 72 hours. Three-way solenoid values controlled by the data system were used to automate the collection of the samples. The sample flow rates were regulated with electronic mass-flow controllers.

Data Analysis

The emission rates of the target analytes were calculated for both the houses and the small-scale chamber experiment assuming that the houses and the chamber were ideal continuously-stirred tank reactors (CSTRs) operating at near steady-state conditions. Losses of the analytes 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:

$$ER = \frac{Va\,(C - C_O)}{A} \tag{1}$$

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 analyte in the house or chamber (µg m^{-3}); C_O is the outdoor air concentration or the chamber inlet air concentration of the analyte (µg m^{-3}); and *A* is the floor area of a house or the exposed surface area of the material in the chamber (m^2).

RESULTS

Concentrations of TVOC, Individual VOCs and Formaldehyde in the Study Houses

The concentrations of TVOC in the four study houses are presented in Figure 1. The relative uncertainty in these measurements as measured by a coefficient of variation is estimated to be less than 40 percent due to the similarity in the compositions of VOCs in the study houses (see below). The median TVOC concentration was 1,580 µg m^{-3} (1.6 mg m^{-3}). For House PH19 only, there was a substantial decrease in TVOC concentration from the first to the second sampling period. However, for Houses PH2, PH19 and PH20, the TVOC concentrations in the final sampling period were lower than the concentrations in the first sampling period.

Data for eight of the 60 original target VOCs were not reported. Three of the compounds, o-xylene, n-octane and decanal, could not be quantified in a number of the samples due to interference caused by co-eluting compounds. Five of the compounds, n-propylbenzene, isopropyl acetate, trichloroethene, tetrachoroethene and 1,4-dichlorobenzene, were not detected in any of the samples.

The remaining 52 target compounds are listed in Table 4 by volatility within each chemical class. The concentrations are presented in parts-per-billion (ppb) by volume since molar-volume concentrations are most relevant with respect to human exposure. If a compound was not detected or if its concentration was less than 1 ppb, the concentration is indicated in the table as <1 ppb. The lower limit of quantitation for most of the target VOCs was approximately 1 - 3 µg m^{-3}, which is typically less than the 1-ppb cutoff point used for reporting. The median concentrations for the entire study are shown in the right-hand column of the table. Fifteen of the target VOCs were included in a large-scale chamber study of common indoor sources of VOCs (Hodgson, 1998). The samples for the chamber study were collected and analyzed using methods that were nearly identical to those employed in this study. With the exception of glycol ethers, the relative uncertainty for the sampling and analysis of these compounds was typically 10 percent or less as determined by a coefficient of variation. The relative uncertainty for ethylene glycol and other glycol ethers ranged up to 36 percent. The relative uncertainty for acetic acid was not determined, but is expected to be as least as high as the uncertainty for the glycol ethers.

The concentration data for the target compounds in are also summarized as SigmaVOC in Table 4. The SigmaVOC values are the sums of the concentrations of the individually quantified compounds. The SigmaVOC values are presented in both molar-volume and mass-volume concentration units. The median SigmaVOC mass-volume concentration was 1,150 µg m^{-3} as compared to the median TVOC concentration of 1,580 µg m^{-3}. The difference between the median TVOC concentration and the median SigmaVOC concentration indicates that, on average, more than 70 percent of the masses of VOCs in the samples were accounted for as individual compounds.

The concentrations of many of the target VOCs were low. Thirty one of the VOCs had median concentrations that were at or below 1 ppb. Fourteen of these compounds had concentrations that were consistently at or below 1 ppb in all houses and sampling periods. These compounds were benzene, ethylbenzene, 1,3,5-trimethylbenzene, naphthalene, 4-phenylcyclohexene, n-pentadecane, n-hexadecane, propylcyclohexane, butylated hydroxytoluene, 4-methyl-2-pentanone (methyl isobutyl ketone), 1-phenylethanone, ethyl acetate, butyl acetate, and benzothiazole.

Table 5 lists the VOCs with the highest concentrations in the four study houses. The 12 most-abundant VOCs for each of the houses were first identified based on their molar-volume concentrations. These compounds were then compiled into a single list of 18 compounds. The table also shows the frequency with which the compounds appeared among the 12 most-abundant compounds in individual houses and the ranges of their maximum concentrations. Seven of the compounds were among the 12 most-abundant VOCs in all four houses. These compounds were alpha-pinene, beta-pinene, 3-carene, ethylene glycol, hexanal, 2-butanone, and acetic acid.

The concentrations of the dominant classes of hydrocarbons are shown in Figure 2. The concentrations for the aromatic, alkane and terpene hydrocarbons are the sums of the molar-volume concentrations of the individual compounds comprising each class. The figure shows that the alkane and terpene hydrocarbons had the highest concentrations. The terpene hydrocarbons were frequently the dominant hydrocarbon class.

The concentrations of the classes of oxidized compounds are shown in Figure 3. These concentrations are the sums of the concentrations of the individual VOCs in each class. The carboxylic acids were generally the dominant class due to the high concentrations of acetic acid.

The glycol ethers and the aldehydes also had relatively high concentrations compared to the other classes.

The formaldehyde concentrations are shown in Figure 4. The relative uncertainty for the sampling and analysis of formaldehyde was not determined; however, it is estimated to be low (*i.e.*, approximately 15 percent or less). The median formaldehyde concentration was 37 ppb, and all of the concentrations were less than 50 ppb.

The concentrations of TVOC, SigmaVOC, selected individual VOCs and formaldehyde in the two, 1997-model, pre-study houses are presented in Table 6. The individual VOCs shown in the table were the most abundant compounds in these samples. The VOC concentrations in House PH13-Pre were, in many cases, about a factor of two lower than the corresponding concentrations in House PH18-Pre. The VOC concentrations in the nine-month old pre-study houses were generally consistent with the concentrations measured in the four study houses in May 1998 (Table 4 and Figures 1 and 4). However, the acetic acid concentrations were a notable exception. The concentrations in the pre-study houses were a factor of ten or more lower than the concentrations measured in the study houses. In fact, the acetic acid concentration in House PH13-Pre was about the same as the outdoor concentration of this compound. The formaldehyde concentrations in Houses PH13-Pre and PH18-Pre were 39 and 65 ppb, respectively.

Specific Emission Rates of TVOC, Individual VOCs and Formaldehyde in the Study Houses

Houses PH2 and PH18 generally had the highest ventilation rates. The HVAC system for House PH18 was equipped with a fresh air inlet and an automatic fan recycle device. House PH19 generally had the lowest and most consistent ventilation rates of about 0.35 h^{-1} (Figure 5). The median ventilation rate for the study was 0.48 h^{-1}.

The area-specific emission rates of TVOC are shown in Figure 6. There is considerable uncertainty in these values due to the high relative uncertainty in the measurement of TVOC concentrations. The median TVOC emission rate was 1,590 $\mu g\ m^{-2}\ h^{-1}$ (1.6 $mg\ m^{-2}\ h^{-1}$). There was no obvious trend of TVOC emission rates decreasing with time throughout the course of the study. However, for three of the houses, PH2, PH19 and PH20, the TVOC emission rate in the final sampling period was less than the emission rate in the initial sampling period. It is not known if these differences are significant. The TVOC emission rates in House PH18 were notably constant.

The area-specific emission rates of the target VOCs are presented in Table 7. The median emission rates for the entire study are shown in the right-hand column of the table. The numerous compounds with low indoor concentrations also had low emission rates.

The specific emission rates for the dominant hydrocarbon classes are shown in Figure 7. Among these classes, the aromatic hydrocarbons had the lowest emission rates. In House PH2, the alkane hydrocarbons with the highest emission rates were n-decane and n-undecane. In this house, there was a substantial decrease in the emission rates of the alkane hydrocarbons in the final sampling period compared to the previous two sampling periods. This was largely due to the decrease in the emission rate of n-decane, a relatively volatile compound. In the other three houses, the alkane hydrocarbons with the highest emission rates were n-dodecane, n-tridecane and n-tetradecane. The combined terpene hydrocarbons had relatively high emission rates in all of the houses.

The specific emission rates for the classes of oxidized compounds are shown in Figure 8. The dominant chemical classes with respect to emission rates were the glycol ethers, aldehydes and carboxylic acids. There were no consistent trends of decreasing emission rates with time with the exception of the glycol ethers in House PH18. There was, however, an increase with time in the emission rates of the carboxylic acids. Acetic acid, the most abundant carboxylic acid, and hexanoic acid both exhibited this trend.

Hexanal was the predominant aldehyde. The emission rates of hexanal are plotted in Figure 9 as a function of time. For Houses PH2 and PH20, the temporal trend was an increase in the rate from the first to the second sampling periods, followed by a decline in the final sampling period. This trend may have been significant within the uncertainty of the emission rate calculations for hexanal. It is notable that the emission rates of hexanal in the final sampling period all fell within a very narrow range of 56 - 65 µg m^{-2} h^{-1}.

The emission rates of acetic acid are plotted in Figure 10 as a function of time. Although the uncertainty in the calculation of the acetic acid emission rates was high, there is an overall trend of acetic acid emission rates increasing with time. In the final sampling period, the rates were in the range of 546 - 808 µg m^{-2} h^{-1}.

The specific emission rates of formaldehyde are shown in Figure 11. The median value was 41 µg m^{-2} h^{-1}. The values for each house varied by less than a factor of two over the course of the study, and there was no consistent trend with time. In the final sampling period, the formaldehyde emission rates were in a narrow range of 37 - 49 µg m^{-2} h^{-1}.

The specific emission rates of TVOC, SigmaVOC, selected individual VOCs and formaldehyde in the two pre-study houses are presented in Table 6. The ventilation rates in Houses PH13-Pre and PH18-Pre were 0.58 and 0.34 h^{-1}, respectively. Thus, even though the concentrations were different, the emission rates calculated for the two houses were in close agreement. With the exception of acetic acid, the VOC emission rates in the nine-month old pre-study houses were generally consistent with the emission rates measured in the four study houses (Table 7 and Figures 6 and 11). The formaldehyde emission rates in the two houses were 62 – 63 µg m^{-2} h^{-1}. These values exceeded the range of values measured in May 1998 in the four equivalent-age study houses.

Specific Emission Rates of VOCs and Formaldehyde from Plywood

The specimen of plywood floor sheeting collected from the manufacturing facility emitted a number of VOCs and formaldehyde. The predominant compounds were terpene hydrocarbons (alpha-pinene, beta-pinene and d-limonene), formaldehyde and higher molecular weight aldehydes (hexanal through decanal), and acetic acid. The emission rates of alpha-pinene, beta-pinene, d-limonene, formaldehyde, hexanal, heptanal, octanal, nonanal and acetic acid at elapsed times of 24, 48 and 72 hours are presented in Table 8. The emission rates of all of the target compounds except formaldehyde decreased by a factor of two or more over this period. At 72-h elapsed time, alpha-pinene, hexanal and acetic acid had the highest emission rates.

DISCUSSION

TVOC

A recent review found that the experimental data do not support the theory that sensory irritancy is associated with the sum of the mass concentrations of individual VOCs at the levels typically encountered in residences and offices (Andersson *et al.*, 1997). Consequently, no scientifically valid guidance can be given with respect to indoor TVOC levels. 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. 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 sample of houses included buildings of all ages. The highest TVOC concentration in House PH19 during the first sampling period was about a factor of four higher than the median concentration for the sample of existing houses. However, the median concentration of TVOC in the four study houses of 1.6 mg m^{-3} was only about twice the value for the existing houses. House PH18 had consistently low TVOC concentrations in the range of 0.95 to 1.3 mg m^{-3}. This house was equipped with a modified HVAC system to provide more ventilation and additionally utilized a low VOC-paint and an upgraded carpet assembly.

Concentrations of TVOC were previously measured in five new site-built houses at four different locations using the same methods as employed in the current study (Hodgson, 1997). Three of the houses were sampled on multiple occasions. The ventilation rates in the houses ranged from 0.07 to 0.4 h^{-1} with a median value close to 0.2 h^{-1}. The TVOC concentrations ranged from 0.65 to 12 mg m^{-3} with a median value of 2.4 mg m^{-3}. The range of TVOC concentrations in the four manufactured houses of 0.8 to 3 mg m^{-3} was generally lower than the range for the site-built houses, and the median concentration was also lower. A portion of this difference might have been related to the higher ventilation rates in the manufactured houses that ranged from 0.4 to 0.8 h^{-1}.

Formaldehyde

Formaldehyde is the only organic compound commonly found in indoor air for which there are 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 (*e.g.*, Gupta *et al.*, 1982; Liu *et al.*, 1991). In addition, formaldehyde is considered to be a possible human carcinogen based on animal studies (Blackwell *et al.*, 1981). Although the human evidence is not pervasive (McLaughlin, 1994), formaldehyde is classified by the U.S. EPA as a toxic air contaminant (EPA, 1993).

A large-scale survey of formaldehyde concentrations in more than 500 manufactured houses (*i.e.*, mobile homes) of all ages located throughout California was conducted in 1984 and 1985 (Sexton *et al.*, 1986 and 1989). The geometric mean concentration of formaldehyde in these houses was 0.072 ppm in the summer and 0.078 ppm in the winter. Maximum concentrations in both seasons exceeded 0.3 ppm. The primary emission source of formaldehyde was recognized to be engineered wood products, such as particle board and plywood, bonded with urea-formaldehyde resins (Meyer, 1979) that were used in relatively large quantities in manufactured houses. The evidence concerning the health effects, indoor concentrations and sources of formaldehyde resulted in the establishment of regulations and guidelines that apply to manufactured houses (HUD, 1984). Plywood wall panels and particleboard floor underlayment are now routinely tested in chambers following ASTM Standard Method E 1333-90 (ASTM, 1990). The chamber concentrations of formaldehyde from the wall panels are limited to 0.2 ppm, and the chamber concentrations from particleboard are limited to 0.3 ppm. It is additionally recommended that the indoor concentration of formaldehyde from all sources including plywood and particle board should not exceed 0.4 ppm. Industry responded to these directives by modifying manufacturing processes to reduce the emissions of formaldehyde from engineered wood products. A recent study has shown that the emissions of formaldehyde from newly manufactured wood products, including various particle boards, medium density fiberboard and hardwood plywood, are typically less than 250 µg m^{-2} h^{-1} (Kelly, 1996).

Guidelines for formaldehyde concentrations in indoor air are now established at relatively low levels. The World Health Organization (WHO) guideline is 0.082 ppm (WHO, 1987). In California, the Department of Health Services recommends 0.05 ppm as an "indoor air concentration guideline", and the Air Resources Board recommends an "action level" of 0.10 ppm with a "target level" of 0.05 ppm or lower (CARB, 1991).

The formaldehyde concentrations in the four houses over the course of the study were all lower than the most restrictive guideline of 0.05 ppm (50 ppb). However, one of the pre-study houses had a slightly higher concentration of 65 ppb. The generally low formaldehyde concentrations in these manufactured houses are probably the consequence of the exclusive use of gypsum board panels for walls and ceilings and the relatively low emissions of formaldehyde from the wood products, such as the plywood floor sheeting and the particle board cabinetry. In fact, the calculated formaldehyde emission rates for the houses were all less than about 70 $\mu g\ m^{-2}\ h^{-1}$ and the median value was 41 $\mu g\ m^{-2}\ h^{-1}$. These emission rates are generally consistent with the formaldehyde emission rates measured for various engineered wood products (Kelly, 1996). They are also within about a factor of two of the lower formaldehyde emission rate measured for the specimen of plywood floor sheeting.

Individual VOCs

Many individual VOCs are classified as irritants and are known to produce sensory irritancy. However, guidance with respect to exposures to individual VOCs only exists for workers in industrial environments. Very few studies have been conducted to assess sensory irritancy or other health effects among the general population that may be caused by exposures to substantially lower concentrations of individual VOCs or combinations of VOCs that are typically encountered in residential environments.

For some classes of commonly occurring VOCs, odor serves as warning mechanism. In one recent study, panels of individuals with and without a normal sense of smell were exposed to homologous series of alcohols and acetates (Cumetto-Muniz and Cain, 1994). The normal panel 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 in the absence of data on irritancy and other health effects. 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 significant adaptation to sensory irritants. Also, the cumulative odor and sensory irritation effects due to exposures to mixtures of compounds are generally unknown.

A number of commonly occurring alcohols, aldehydes and carboxylic acids produce objectionable odors at relatively low concentrations. Some of these compounds have been associated with odor complaints in buildings. Standardized olfactory thresholds (Devos *et al.*, 1990) for selected alcohols, aldehydes and carboxylic acids are presented in Table 9. There are large standard errors associated with these values because of experimental differences and the wide variability in human response. The ranges of concentrations measured in the four houses are compared to the odor thresholds. The concentrations of hexanal frequently were either near or exceeded the odor threshold of 14 ppb. The odor thresholds for octanal and nonanal are 1 ppb or less. The measured concentrations of these compounds almost always exceeded these values. The odor threshold of acetic acid of 140 ppb was approached in all of the houses during the second sampling period and was exceeded in all of the houses during the final sampling period. Thus, it is expected that many individuals would be able to detect objectionable odors in the houses due to the elevated concentrations of the aldehydes and acetic acid.

Brown *et al.* (1994) summarized the concentration data for a number of VOCs commonly encountered in indoor air from the literature. These investigators calculated weighted average geometric mean concentrations for 80 compounds detected in established dwellings. Twenty-nine of the compounds were included in the list of target compounds for this study. The concentration ranges and the median concentrations of these 29 compounds in the four test houses are compared to the summarized literature data in Table 10. The concentrations of a number of the compounds in the test houses were below or near the typically measured values. Compounds which had notably elevated concentrations in the study houses compared to the literature data included the normal alkane and the terpene hydrocarbons, n-decane, n-undecane, n-dodecane, and n-tetradecane, alpha-pinene and beta-pinene. Other compounds with elevated concentrations in the study houses were 1-butanol, hexanal, nonanal, and 2-butanone.

Lindstrom *et al.* (1995) measured concentrations of carbonyl compounds including hexanal in nine, newly constructed, site-built houses. The houses were located in the same area and were of similar size and quality. All of the houses had oriented strand board or plywood floor sheeting. Prior to occupancy, the hexanal concentrations were in a range of 6 to 79 µg m^{-3} with a median value of 47 µg m^{-3}. Following occupancy, the hexanal concentrations were in a range of 22 to 106 µg m^{-3} with a median value of 50 µg m^{-3}. These values are generally similar to the hexanal concentrations measured in the four study houses of 32 - 106 µg m^{-3}.

Sources of VOCs

Some of the known indoor sources of selected VOCs are listed in Table 11. These sources were identified in a small- and large-scale chamber study of latex paints and carpet and sheet vinyl flooring materials (Hodgson, 1998). Many conventional latex wall paints contain ethylene glycol and/or 1,2-propanediol (propylene glycol) as solvents and Texanol® isomers as a coalescing aid. Latex paints may also emit 2-(2-butoxyethoxy)ethanol, another glycol ether. The emissions of glycol ethers and Texanol® from latex paints applied to gypsum wall board can persist at elevated levels for at least several months (Chang *et al.*, 1997; Hodgson, 1998). Residential carpeting is a source of styrene and 4-phenylcyclohexene. This latter compound is the predominant cause of the "new carpet" odor. The emissions of styrene decease rapidly with time while the emissions of 4-phenylcyclohexene are considerably more persistent. Bonded urethane carpet cushions can be a source of butylated hydroxytoluene and complex mixtures of unsaturated hydrocarbons. Sheet vinyl flooring is a source of a number of compounds. These compounds may include n-decane, n-tridecane, toluene, 1,2,4-trimethylbenzene, phenol, TXIB® and higher molecular-weight alkyl substituted benzenes. Generally, the emissions of the less volatile components, such as phenol and TXIB®, persist for relatively long time periods (Hodgson, 1998).

The data show that indoor air quality in the study houses was relatively unaffected by some of the common sources of VOCs. For example, 4-phenylcyclohexene from was not detected above 1 ppb, and butylated hydroxytoluene from carpet cushions and TXIB® from vinyl flooring were only present at very low concentrations.

The data also suggest that indoor air quality in all of the study houses was impacted by the same few sources of VOCs. At least a portion of the normal alkane hydrocarbons, such as n-tridecane and n-tetradecane, detected in the air samples may have originated from sheet vinyl flooring, although there may have been other sources of these commonly occurring compounds. Wood and engineered wood products emit terpene hydrocarbons. The composition of the terpene hydrocarbons is determined by the species of wood (Baumann *et al.*, In Press). The chamber results showed that the plywood was a source of alpha-pinene, beta-pinene and d-limonene, but not a source of 3-carene. Thus, the plywood sheeting used as the subfloor may have been a significant source of some, but not all of the terpene hydrocarbons detected in the houses. Engineered wood products emit hexanal and other aldehydes including heptanal, octanal, nonanal and 2-furancarboxaldehyde (Baumann *et al.*, In Press). This was also shown by the chamber results for the plywood. Therefore, it is likely that engineered wood products in the houses were the primary source of the aldehydes. The predominant wood products used in the houses included the plywood floor sheeting, the roof decking, and interior components such as the kitchen and bathroom cabinetry and wainscoting.

The source of the acetic acid in the study houses is less certain. The emission rate of acetic acid increased with time in all four houses, and by the end of the study, acetic acid was by far the predominant compound. The source had to be a material used in large quantity since the mass emission of acetic acid in the houses at the end of the study was calculated to be in the range of two to three grams per day. Based on the chamber results for the plywood, one possible source is the plywood floor sheeting. However, it is notable that the acetic acid concentrations in the pre-study houses, which also had plywood floors, were low. Another possible source of acetic acid is silicone-based adhesives and caulks.

Source Substitution

The previously cited small- and large-scale chamber study of latex paint combinations and carpet and vinyl flooring assemblies concluded that the most effective way to reduce VOC levels and occupant exposures to VOCs in new or renovated buildings is to utilize low-emitting materials (Hodgson, 1998).

The source substitution treatments that were attempted in the current study consisted of utilizing several low-emitting, large-volume materials in selected houses. A synthetic fiber carpet cushion and a good quality Nylon carpet were installed in Houses PH18 and PH20. Both of these materials have generally been found to have low emissions of VOCs relative to other possible materials in these categories (Hodgson *et al.*, 1993; Schaeffer *et al.*, 1996; Hodgson, 1998). A new-generation, low-VOC, latex paint was applied to the textured gypsum wallboard in Houses PH18, PH19 and PH20. These houses additionally utilized pre-finished, vinyl covered, gypsum wallboard in a number of the rooms, including the bedrooms. House PH2 utilized substantially more textured gypsum wallboard that was painted with a conventional latex paint. The kitchen and bathroom floors in House PH2 were finished with ceramic tile rather than sheet vinyl flooring which was used extensively in the other houses.

The effects of the source substitution treatments were difficult to evaluate for several reasons. Most significantly, the houses contained a number of other sources of VOCs with varying source strengths that tended to mask the effects of the treatments. Also, the study did not have direct control over the final finishing of the houses after they left the manufacturing facility. This meant, for example, that conventional latex paints were possibly used to decorate the houses, which were originally painted with low-VOC paints. Nevertheless, there were several distinctions that could be attributed to the substituted sources. House PH2 with ceramic tile had lower emission rates of n-tridecane, n-tetradecane and phenol that are emitted by sheet vinyl flooring. Houses PH18 and PH20 with the low-emitting carpet assembly had lower emission rates of butylated hydroxytoluene that is emitted by bonded urethane carpet cushions. Houses PH18, PH19 and PH20 with the low-VOC paint had lower emission rates of Texanol® that is emitted by conventional latex paints.

CONCLUSIONS AND RECOMENDATIONS

The concentrations of VOCs in the study houses were not abnormally elevated. Most significantly, the formaldehyde concentrations were lower than the most restrictive guidelines for this compound. Concentrations of TVOC generally were within a factor of about two higher than concentrations typically measured in existing houses. In addition, the TVOC concentrations were somewhat lower than those measured in several new site-built houses. The house with the modified HVAC system and several lower emitting materials had consistently low TVOC concentrations that were near 1 mg m^{-3}. There were, however, a few individual VOCs that exceeded their odor thresholds. These compounds were hexanal, octanal, nonanal and acetic acid. Elevated concentrations of these compounds could result in odor complaints. The compounds are additionally significant as indoor air contaminants because they are known sensory irritants. The source of the aldehydes is most likely engineered wood products, such as the plywood sheeting used for the subfloor and possibly other structural or interior components. The source of the acetic acid is uncertain. The effects of the source substitution treatments on indoor VOC concentrations were observable but turned out to be relatively minor due to the predominance of other sources.

In order to assure occupant satisfaction and comfort with respect to air quality, a continued effort should be made to identify and reduce the sources of potentially objectionable VOCs in the construction and finishing of new manufactured houses. The use of low emitting or low impact products, such as new-generation, low-VOC, latex paints and good quality carpeting materials, should be continued. Source substitution treatments should be attempted for other materials as well. High priority should be given to identifying and reducing the source of acetic acid. Further study of the emissions of hexanal and other aldehydes from wood products is also needed. It may be possible to identify wood products with lower emission rates of these compounds. Alternately, it may be possible to develop strategies to reduce or isolate the emissions of these compounds from standard products. Although the impact of ventilation on indoor air quality was not specifically addressed as part of this study, there is a substantial need to understand the relationships among ventilation rates, various ventilation strategies, energy consumption for heating and cooling, and the emission rates and concentrations of VOC contaminants.

REFERENCES

Andersson, K., J.V. Bakke, O. Bjorseth, C.-G. Bornehag, G. Clausen, J.K. Hongslo, M. Kjellman, S. Kjaergaarrd, F. Levy, L. Molhave, S. Skerfving and J. Sundell. 1997. TVOC and health in non-industrial indoor environments. Report from a Nordic scientific consensus meeting at Langholmen in Stockholm, 1996. *Indoor Air* **7**: 78-91.

ASTM. 1990. *ASTM Standard E 1333-90, Standard Test Method for Determining Formaldehyde Levels from Pressed Wood Products Under Defined Test Conditions Using a Large Chamber*. American Society for Testing and Materials, Philadelphia, PA.

ASTM. 1997. *ASTM Standard D 5116-97, Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions From Indoor Materials/Products*. American Society for Testing and Materials, Philadelphia, PA.

Baumann, M.G.D., S.A. Batterman and G.-Z. Zhang. In Press. Terpene emissions from particleboard and medium-density fiberboard products. *Forest Products Journal*.

Blackwell, M., H. Kang, A. Thomas and P. Infante. 1981. Formaldehyde: evidence of carcinogenicity. *American Industrial Hygiene Association J.* **42:** A-34 – A-46.

Brown, S.K., M.R. Sim, M.J. Abramson and C.N. Gray. 1994. Concentrations of volatile organic compounds in indoor air – A review. *Indoor Air* **4:** 123-134.

CARB. 1991. *Indoor Air Quality Guideline No. 1: Formaldehyde in the Home*. California Air Resources Board, Research Division, Sacramento, CA.

Chang, J.C.S., B.A. Tichenor, Z. Guo and K.A. Krebs. 1997. Substrate effects on VOC emissions from a latex paint. *Indoor Air* **7:** 241-247.

Cumetto-Muniz, J.E. and W.S. Cain. 1994. Perception of odor and nasal pungency from homologous series of volatile organic compounds. *Indoor Air* **4:** 140-145.

Devos, M., F. Patte, J. Rouault, P. Laffort and L.J. Gmert. 1990. *Standardized Human Olfactory Thresholds*. Oxford University Press, New York, NY.

ECA-IAQ. 1997. Report No. 19. Total volatile organic compounds (TVOC) in indoor air quality investigations. Report EUR 17775 EN, European Collaborative Action, Indoor Air Quality & Its Impact on Man.

EPA (U.S. Environmental Protection Agency). 1993. *Integrated Risk Information System.*

Girman, J.R., S.E. Womble and E.L. Ronca. 1995. Developing baseline information on buildings and indoor air quality (BASE'94): Part II – Environmental pollutant measurements and occupant perceptions. *Proceedings of Healthy Buildings '95*, Milan Italy, Vol. 3, pp. 1311-1316.

Gupta, K.C., A.G. Ulsamer and P.W. Preuss. 1982. Formaldehyde in indoor air: sources and toxicity. *Environment International* **8:** 349-358.

Heller, S.R. and G.W.A. Milne. 1978. *EPA/NIH Mass Spectral Data Base*. U.S. Nat. Bur. Stand., Nat Stand. Ref. Data Ser., 63, U.S. Government Printing Office, Washington D.C.

Hodgson, A.T., J.D. Wooley and J.M. Daisey. 1993. Emissions of volatile organic compounds from new carpets measured in a large-scale environmental chamber. *J. Air Waste Manage. Assoc.* **43:** 316-324.

Hodgson, A.T. 1995. A review and a limited comparison of methods for measuring total volatile organic compounds in indoor air. *Indoor Air* **5:** 247-257.

Hodgson, A.T. 1997. Indoor air quality in new energy-efficient houses. *Center for Building Science News*, PUB-731 Rev. Spring 1997-10000, Lawrence Berkeley National Laboratory.

Hodgson, A.T. 1998. Common indoor sources of volatile organic compounds: emission rates and techniques for reducing consumer exposures. Final Report to California Air Resources Board, Contract No. 95-302. Report LBNL-42402, E.O. Lawrence Berkeley National Laboratory, Berkeley, CA.

HUD (U.S. Department of Housing and Urban Development). 1984. Manufactured Home Construction and Safety Standards; Final Rule. 24 CFR Part 3280. *Federal Register*, August 9, 1984, **49**(155): 31996-32013.

Kelly, T.J. 1996. Determination of formaldehyde and toluene diisocyanate emissions fron indoor residential sources. Battelle, Columbus, OH, Final Report to California Air Resources Board, Contract No. 93-315.

Lindstrom, A.B., D. Proffitt and C.R. Fortune. 1995. Effects of modified residential construction on indoor air quality. *Indoor Air* **5:** 258-269.

Liu, K.-S., F.-Y. Huang, S.B. Hayward, J. Wesolowski and K. Sexton. 1991. Irritant effects of formaldehyde exposure in mobile homes. *Environmental Health Perspectives* **94:** 91-94.

Maroni, M. and B. Lundgren. 1998. Assessment of the health and comfort effects of chemical emissions from building materials: the state of the art in the European Union. *Indoor Air* Suppl. **4:** 26-31.

McLaughlin, J.K. 1994. Formaldehyde and cancer: a critical review. *Int. Arch. Occup. Environ. Health* **66:** 295-301.

Meyer, B. 1979. *Urea-formaldehyde Resins*. Addison-Wesley Publishing Co., Reading, MA.

NRC (National Research Council). 1981. *Formaldehyde and Other Aldehydes*. National Academy Press (National Academy of Sciences), Washington, D.C.

Riggan, R.M. 1984. Compendium of methods for the determination of toxic organic compounds in ambient air. U.S. EPA Report EPA-600/4-84-041, Environmental Monitoring Systems Laboratory, Research Triangle Park, NC.

Schaeffer, V.H., B. Bhooshan, S.-B. Chen, J.S. Sonenthal and A.T. Hodgson. 1996. Characterization of volatile organic chemical emissions from carpet cushions. Screening measurements with carpet cushions. *J. Air & Waste Manage. Assoc.* **46:** 813-820.

Sexton, K., K.-S. Liu and M.X. Petreas. 1986. Formaldehyde concentrations inside private residences: a mail-out approach to indoor air monitoring. *J. Air Pollution Control Assoc.* **36:** 698-704.

Sexton, K., M.X. Petreas and K.-S. Liu. 1989. Formaldehyde exposures inside mobile homes. *Environ. Sci. Technol.* **23:** 985-988.

Wallace, L., E. Pellizarri and C. Wendel. 1991. Total volatile organic concentrations in 2700 personal, indoor, and outdoor air samples collected in the US EPA Team studies. *Indoor Air* **1:** 465-477.

WHO. 1987. *Air Quality Guidelines for Europe*. WHO Regional Publications, European Series No. 23. World Health Organization, Regional Office for Europe, Copenhagen, Denmark.

Winberry, W.T., N.T. Murphy and R.M. Riggan. 1988a. Method TO-1. Determination of volatile organic compounds in ambient air using Tenax adsorption and gas chromatography/mass spectrometry (GC/MS). In: Compendium of methods for the determination of toxic organic compounds in ambient air. U.S. EPA Report, Environmental Monitoring Systems Laboratory, Research Triangle Park, NC.

Winberry, W.T., N.T. Murphy and R.M. Riggan. 1988b. Method TO-11. Determination of formaldehyde in ambient air using adsorbent cartridge followed by high performance liquid chromatography (HPLC). In: Compendium of methods for the determination of toxic organic compounds in ambient air. U.S. EPA Report, Environmental Monitoring Systems Laboratory, Research Triangle Park, NC.

Wolkoff, P., G.D. Nielsen, L.F. Hansen, O. Albrechtsen, C.R. Johnsen, J.H. Heinig, C. Franck and P.A. Nielsen. 1991. A study of human reactions to emissions from building materials in climate chambers. Part II: VOC measurements, mouse bioassay, and decipol evaluation in the 1-2 mg/m^3 TVOC range. *Indoor Air* **1:** 389-403.

Wolkoff, P. and P. Nielsen. 1996. A new approach for indoor climate labeling of building materials – emission testing, modeling, and comfort evaluation. *Atmospheric Environment* **30:** 2679-2689.

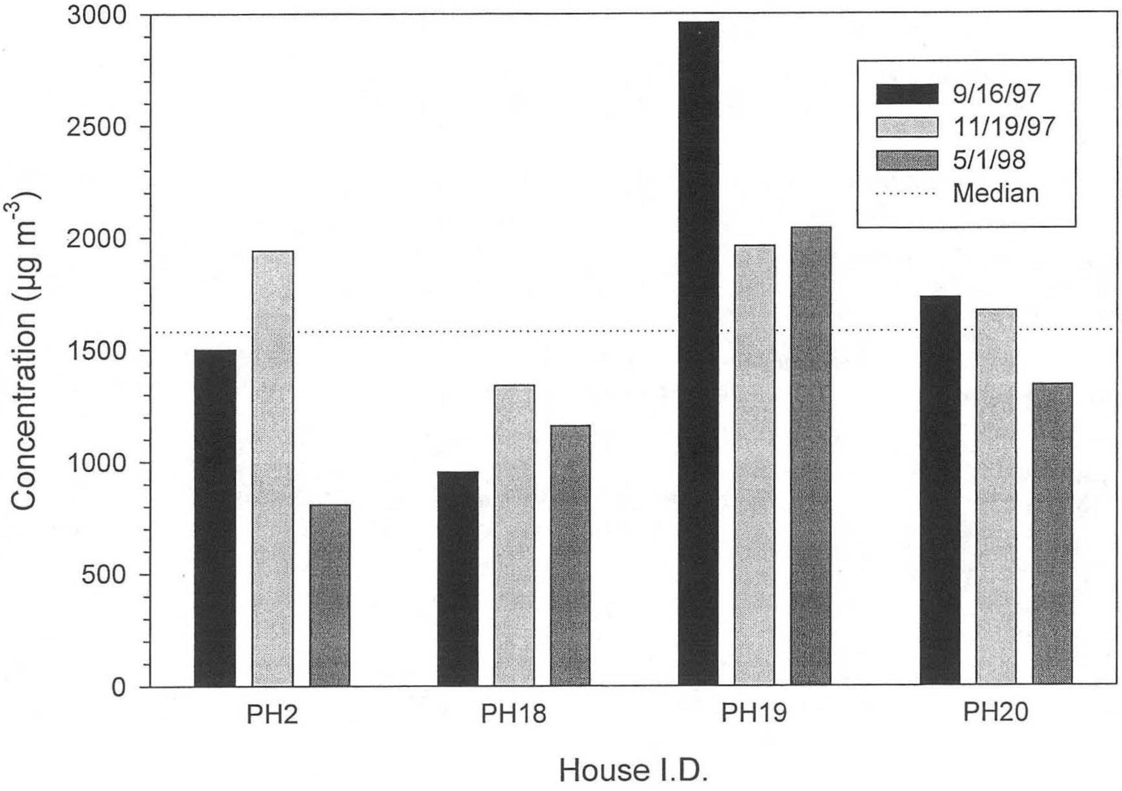

Figure 1. Concentrations of TVOC in the four study houses on three samping dates between September 1997 and May 1998.

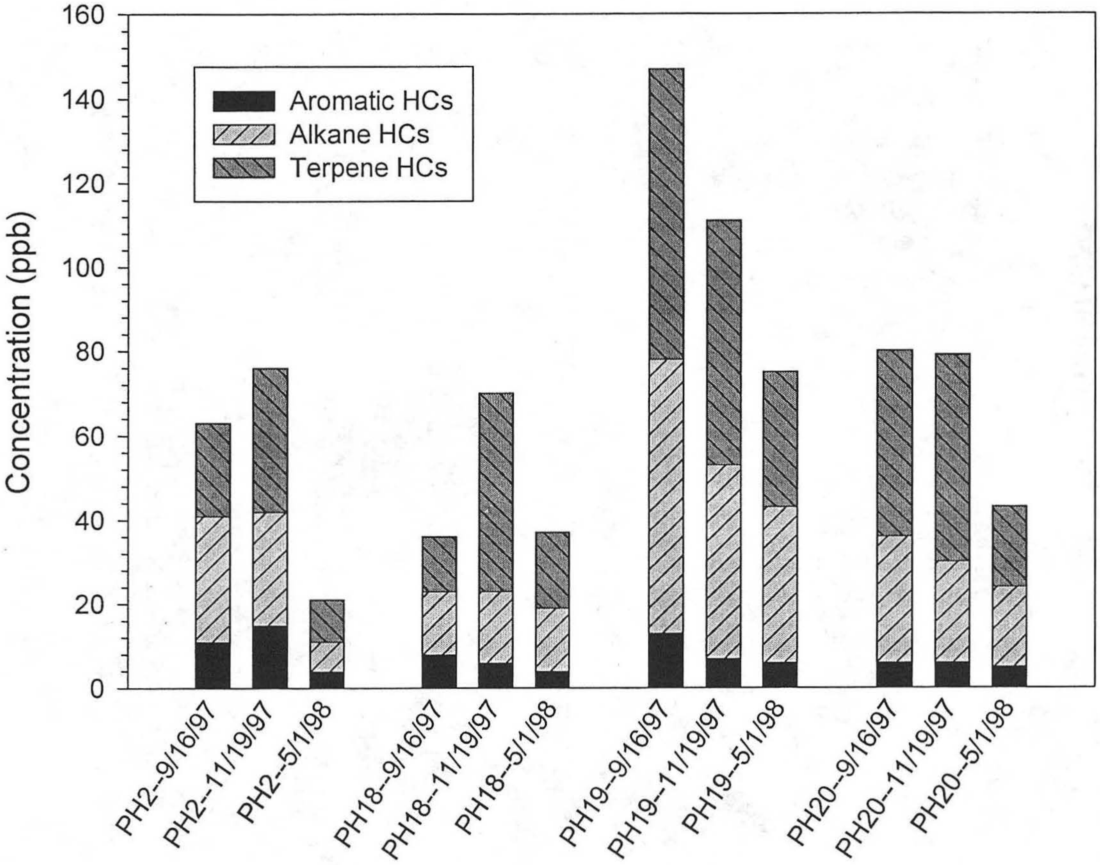

Figure 2. Concentrations (ppb) of predominant hydrocarbons by class in the four study houses on three sampling dates between September 1997 and May 1998.

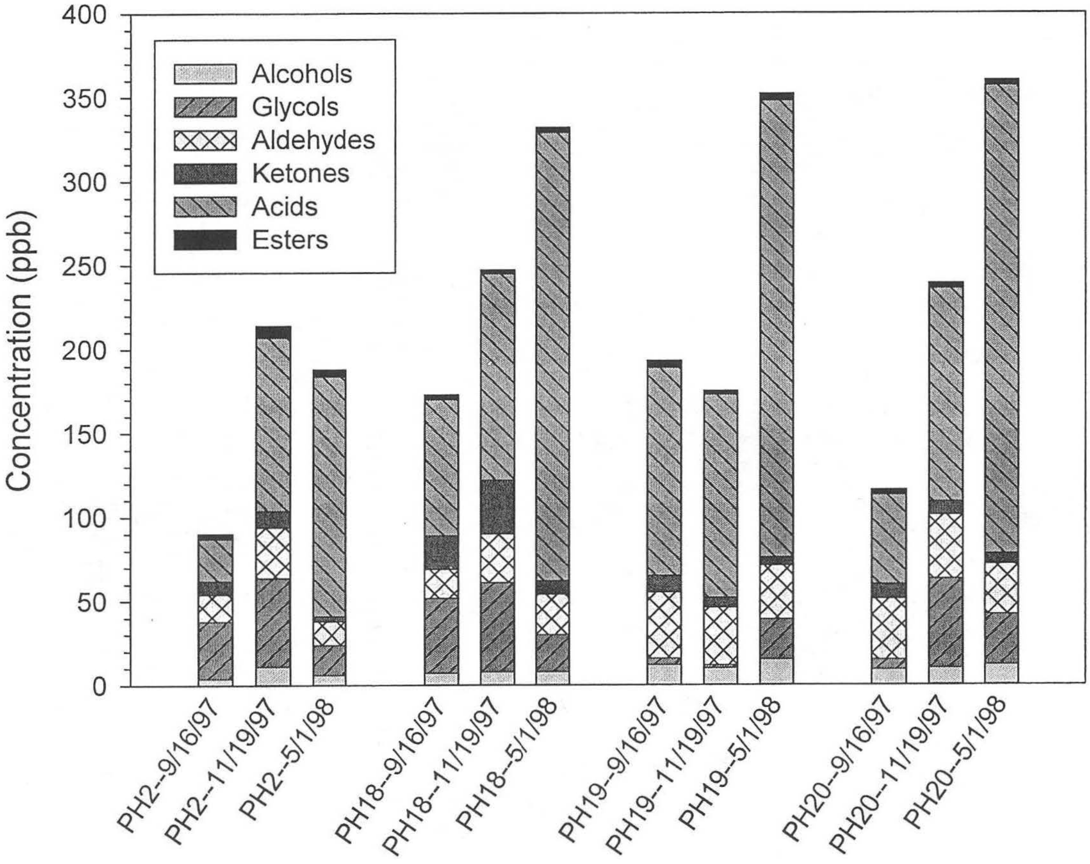

Figure 3. Concentrations (ppb) of oxidized compounds by class in the four study houses on three sampling dates between September 1997 and May 1998.

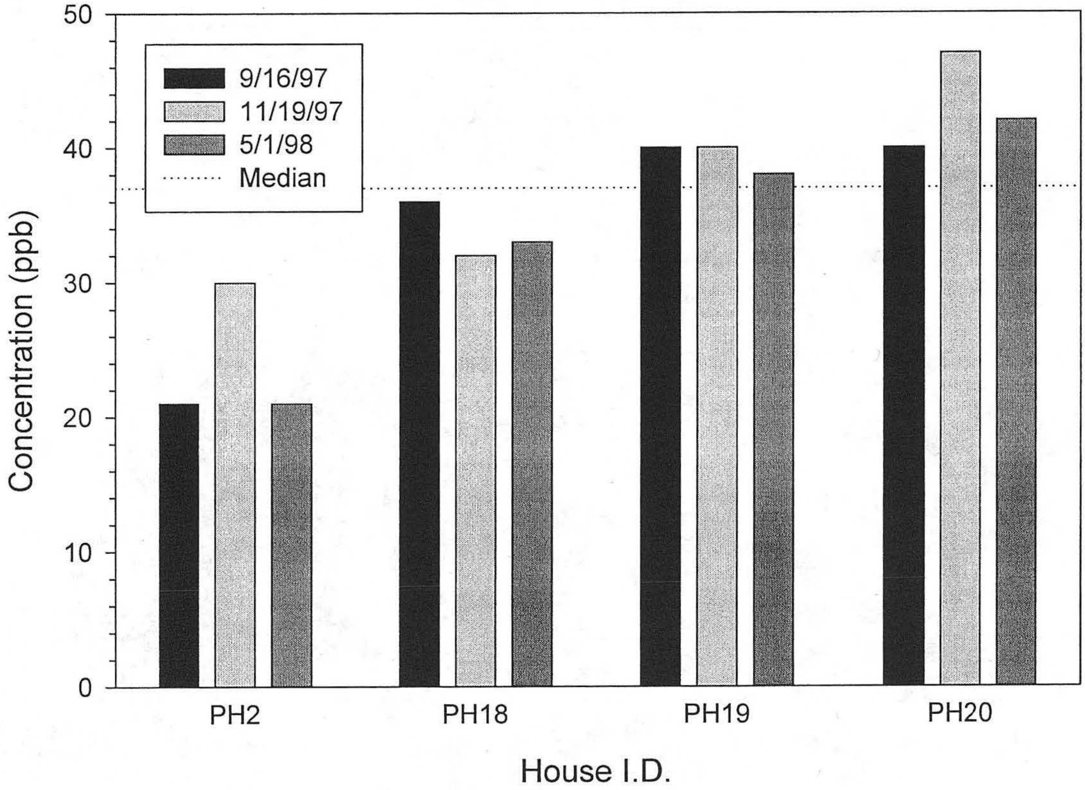

Figure 4. Concentrations of formaldehyde (ppb) in the four study houses on three samping dates between September 1997 and May 1998.

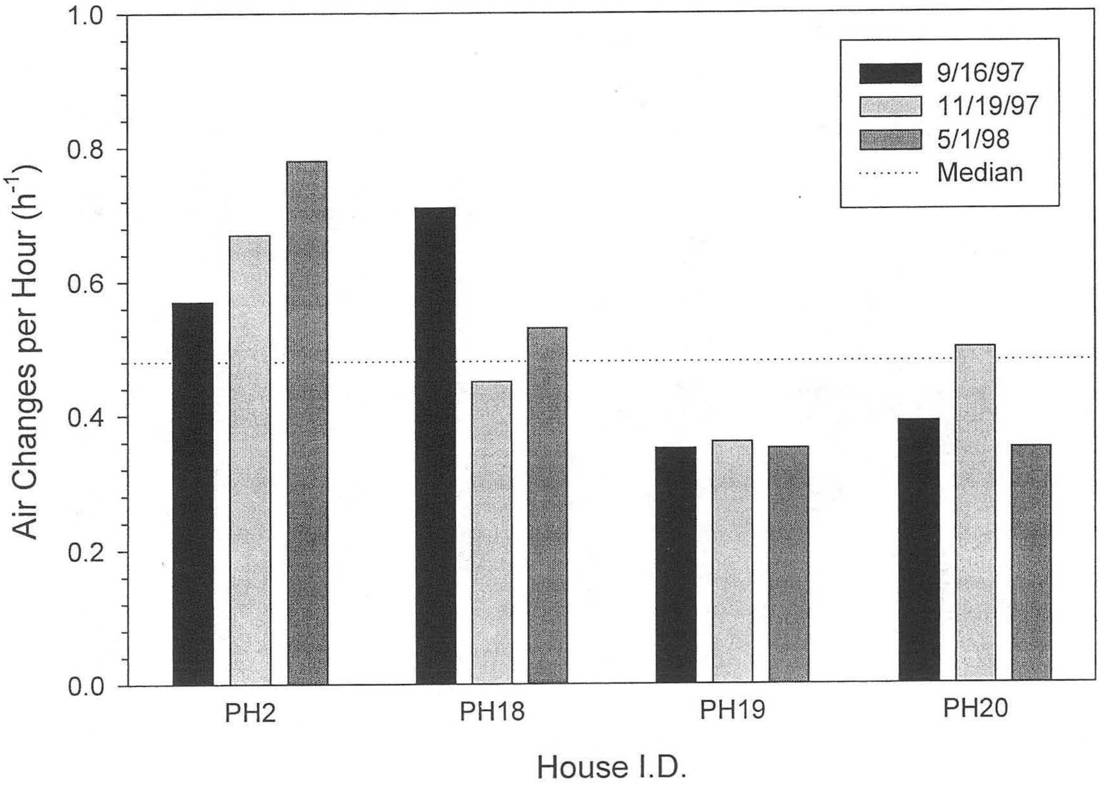

Figure 5. Ventilation rates in the four study houses on three sampling dates between September 1997 and May 1998.

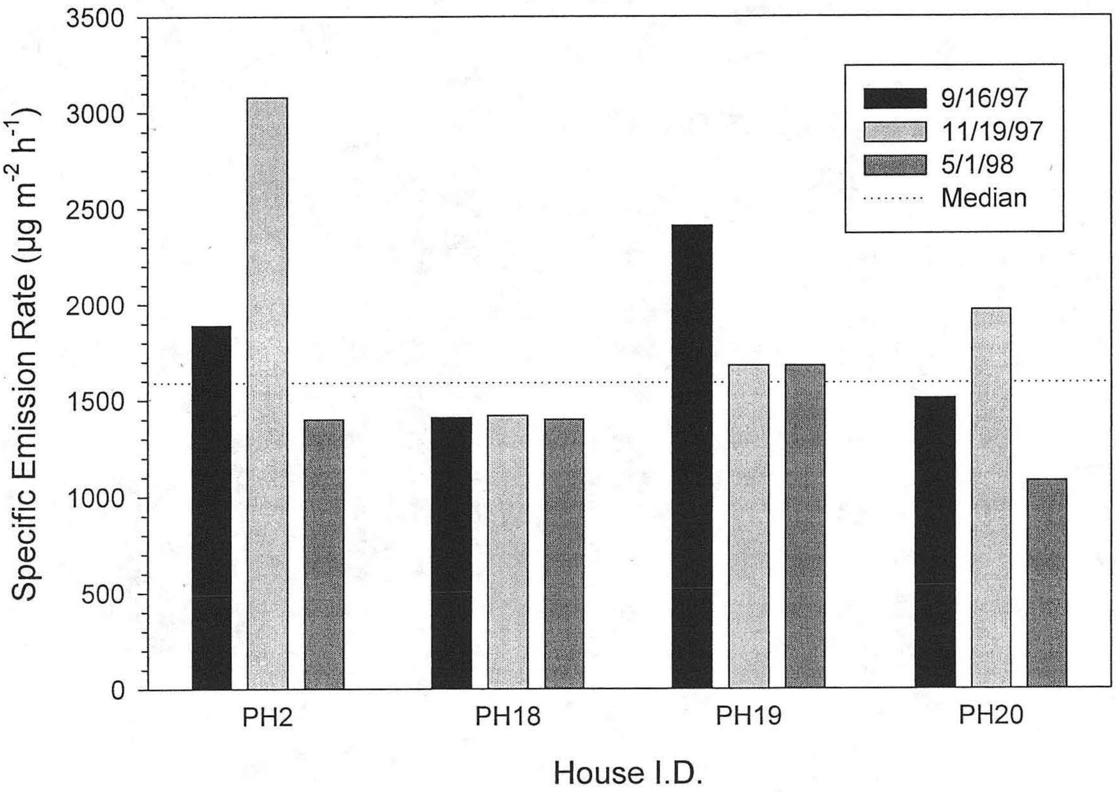

Figure 6. Specific emission rates of TVOC in the four study houses on three sampling dates between September 1997 and May 1998.

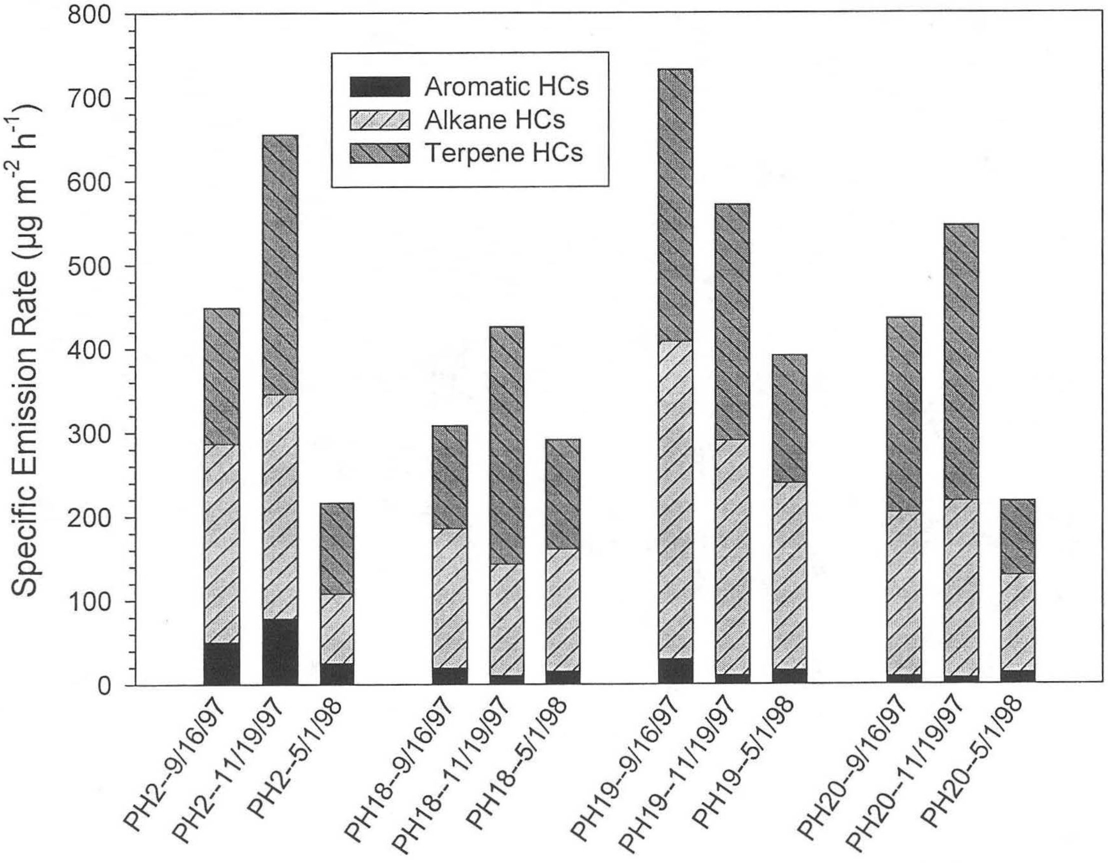

Figure 7. Specific emission rates of predominant hydrocarbons by class in the four study houses on three sampling dates between September 1997 and May 1998.

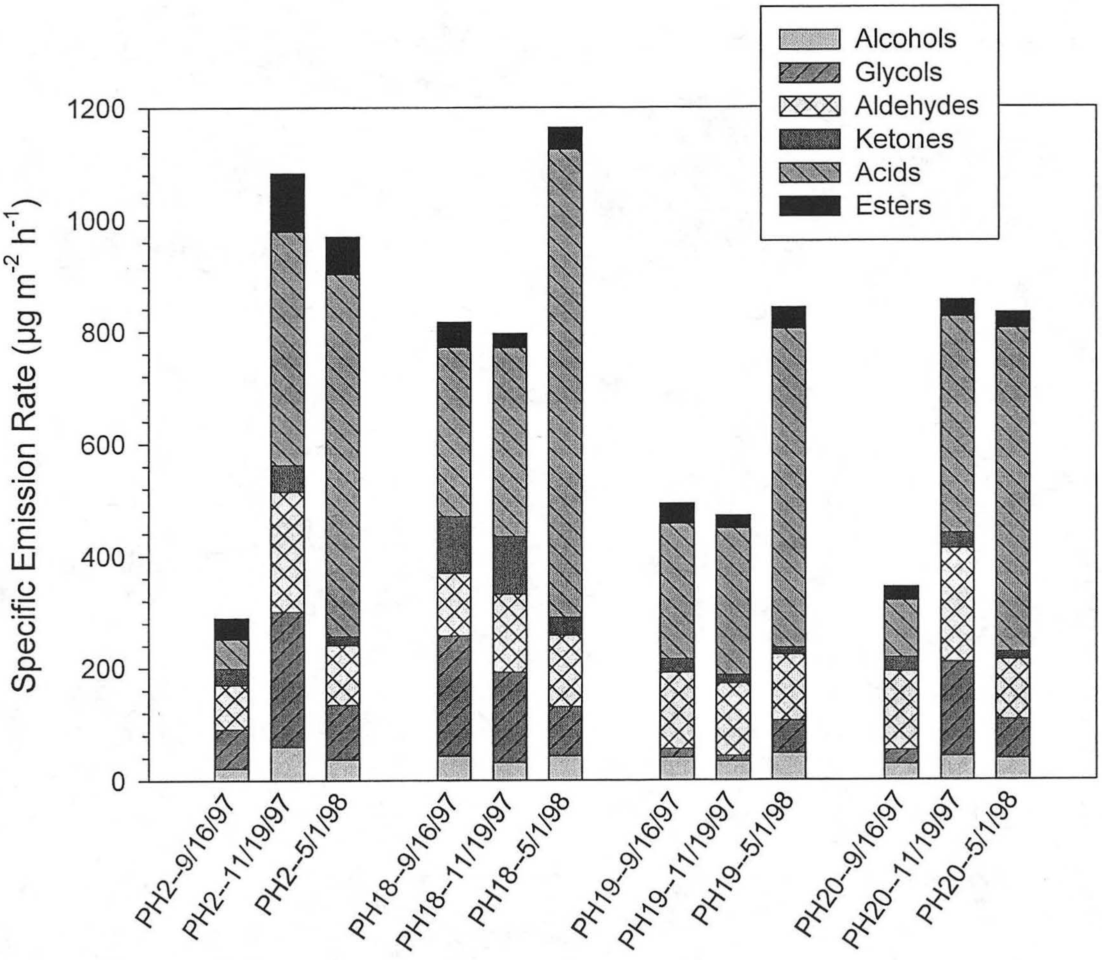

Figure 8. Specific emission rates of oxidized compounds by class in the four study houses on three sampling dates between September 1997 and May 1998.

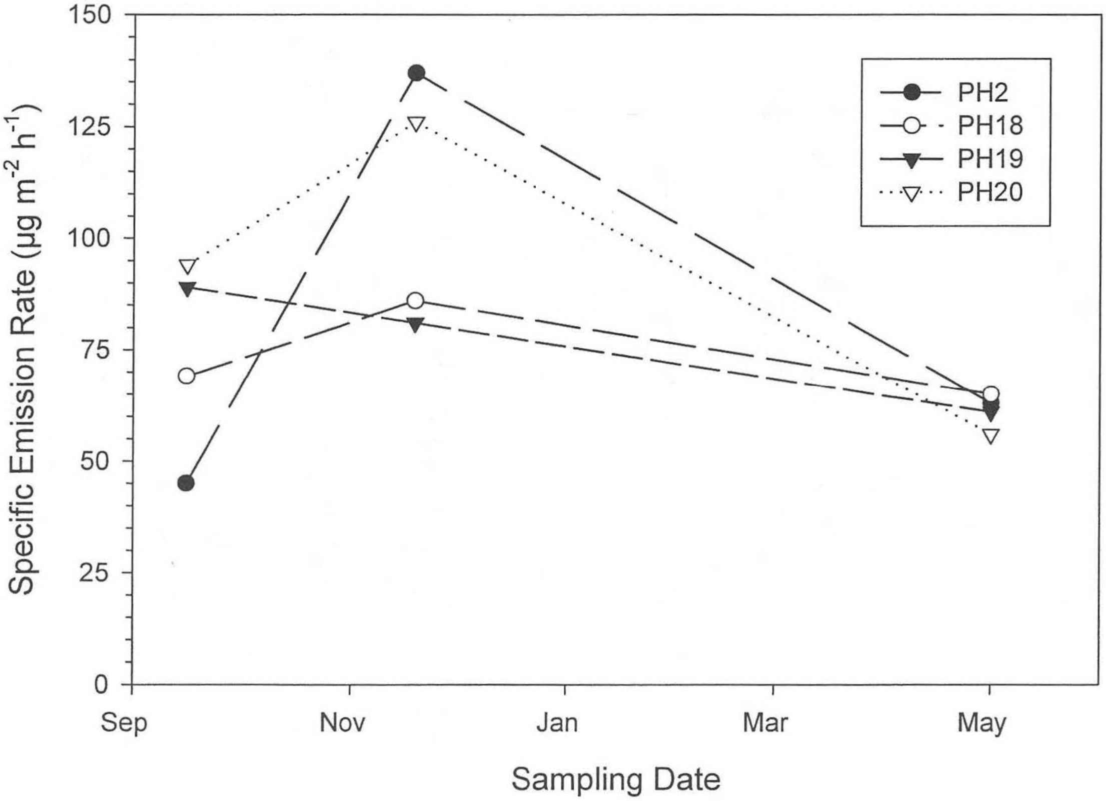

Figure 9. Specific emission rates of hexanal in the four study houses on three sampling dates between September 1997 and May 1998.

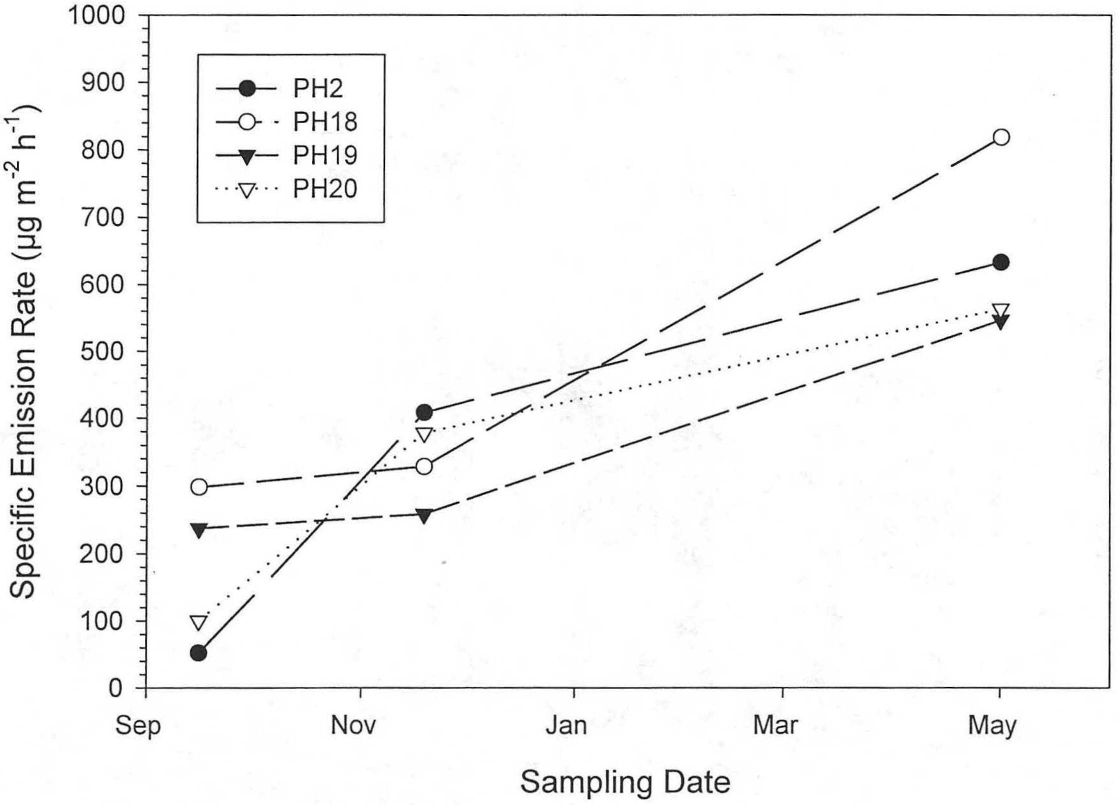

Figure 10. Specific emission rates of acetic acid in the four study houses on three sampling dates between September 1997 and May 1998.

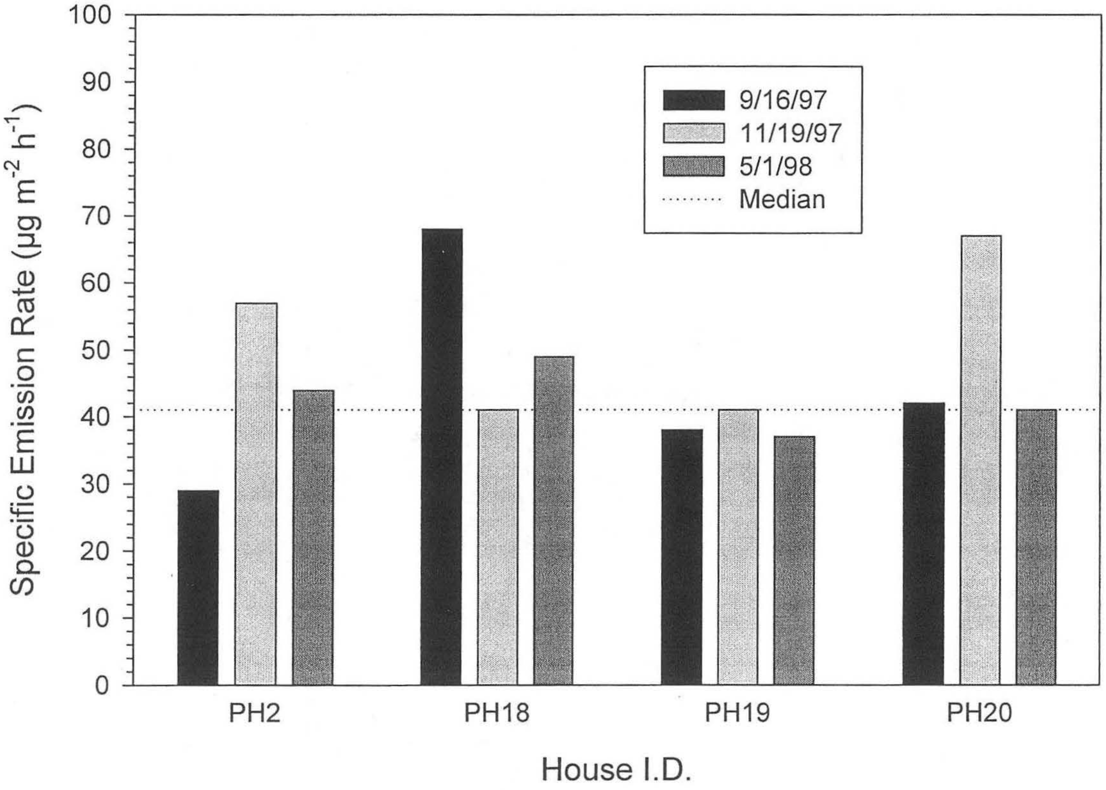

Figure 11. Specific emission rates of formaldehyde in the four study houses on three sampling dates between September 1997 and May 1998.

Table 1. Specifications for the four study houses.

Parameter	PH2	PH18	PH19	PH20
Floor area, m^2	112	169	141	131
No. bedrooms/bathrooms	2 / 2	4 / 2	3 / 2	3 / 2
Volume, m^3	273	412	344	320
Ducted fresh air inlet with auto fan re-cycle, Yes/No	No	Yes	No	No
Carpet area, m^2	72	128	94	96
Sheet vinyl floor area, m^2	0	29	29	21
Ceramic tile floor area, m^2	28	0	0	0
Low VOC paint, Yes/No	No	Yes	Yes	Yes
Low emitting carpet, Yes/No	No	Yes	No	Yes

Table 2. Specifications for the instrumentation used for the analysis of VOCs.

Component	Specifications & Operating Parameters
Analytical column	DB-1701 (J&W Scientific, Inc.) 30 m x 0.25 mm ID x 1.0 µm film
Carrier gas	Helium @ ~1 cm^3 sec^{-1}
Concentrator	CP-4020 TCT, (Chrompack) Tube desorb temp: 6.5 min @ 250° C Trap inject temp: 200° C
GC oven	Model 5890 II (Hewlett-Packard Corp.) 40° C (5 min) 40 - 225° C @ 5° C min^{-1} 225° C (7 min)
Mass spectrometer	Model 5970B (Hewlett-Packard Corp.) SCAN mode: *m/z* 30 - 350 @ 1.9 scans sec^{-1}

Table 3. Specifications and operating parameters for the small-scale chambers.

Parameter	Value
Chamber material	316 Stainless steel
Chamber volume, m^3	10.5×10^{-3}
Gas	Humidified N_2
Inlet gas flow rate, m^3 h^{-1}	$6.0 \pm 0.3 \times 10^{-2}$
Ventilation rate, h^{-1}	5.7 ± 0.3
Temperature, °C	23 ± 1
Relative humidity, %	50 ± 10
Sample surface area, m^2	7.4×10^{-3}
Sample loading ratio, m^2 m^{-3}	0.70
Exposure period, h	72
Sample collection times, h	24, 48, 72

Table 4. Concentrations (ppb) of individual VOCs in the four study houses on 9/16/97, 11/19/97 and 5/1/98.

		Concentration (ppb)												
	Chemical		PH2			PH18			PH19			PH20		Median
Compound	Class*	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	Value
Benzene^T	AromaHC	<1	1	1	<1	<1	1	<1	1	1	<1	1	<1	1
Toluene^T	AromaHC	2	3	1	6	3	2	4	2	2	3	3	2	2
Ethylbenzene^T	AromaHC	<1	1	<1	<1	1	<1	1	<1	<1	<1	<1	<1	<1
m/p-Xylene^T	AromaHC	1	2	1	1	1	1	3	1	1	1	1	1	1
Styrene^T	AromaHC	1	2	1	<1	1	1	1	1	1	1	1	1	1
1,3,5-Trimethylbenzene	AromaHC	1	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
1,2,4-Trimethylbenzene^T	AromaHC	4	4	1	<1	<1	<1	2	1	1	<1	<1	<1	1
Naphthalene^T	AromaHC	<1	<1	<1	<1	<1	<1	1	1	1	<1	<1	<1	<1
4-Phenylcyclohexene	AromaHC	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
n-Heptane	AlkaneHC	1	1	<1	1	1	1	5	4	4	1	1	2	1
n-Nonane	AlkaneHC	3	2	<1	<1	1	<1	3	1	<1	1	<1	<1	1
n-Decane	AlkaneHC	16	14	1	1	1	<1	8	4	2	2	1	1	1
n-Undecane	AlkaneHC	7	7	2	<1	<1	<1	3	2	1	1	1	<1	1
n-Dodecane	AlkaneHC	1	1	1	2	3	2	10	8	6	5	4	3	3
n-Tridecane	AlkaneHC	1	1	1	6	7	6	21	17	12	12	10	7	7
n-Tetradecane	AlkaneHC	1	1	1	4	4	5	13	10	11	6	6	5	5
n-Pentadecane	AlkaneHC	<1	<1	<1	<1	<1	<1	1	<1	1	1	<1	<1	<1
n-Hexadecane	AlkaneHC	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Methylcyclohexane	CyclicHC	<1	2	<1	1	<1	<1	1	<1	1	1	<1	2	1
Propylcyclohexane	CyclicHC	1	1	<1	<1	<1	<1	1	<1	<1	<1	<1	<1	<1
Butylcylohexane	CyclicHC	2	2	<1	<1	<1	<1	1	<1	<1	<1	<1	<1	<1

Table 4, Continued. Concentrations (ppb) of individual VOCs in the four study houses on 9/16/97, 11/19/97 and 5/1/98.

		Concentration (ppb)												
	Chemical	PH2			PH18			PH19			PH20			Median
Compound	Class*	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	Value
alpha-Pinene	TerpHC	13	19	5	9	31	10	35	32	15	23	25	9	17
Camphene	TerpHC	<1	1	<1	<1	1	<1	2	1	1	1	1	<1	1
beta-Pinene	TerpHC	3	6	2	2	7	3	11	8	5	7	6	3	5
3-Carene	TerpHC	3	6	2	1	5	2	15	11	7	9	10	4	5
d-Limonene	TerpHC	2	3	1	1	3	2	7	5	4	5	5	3	3
1-Butanol	Alcohol	2	6	3	3	4	1	4	4	5	3	4	4	4
2-Ethyl-1-hexanol	Alcohol	1	2	1	1	1	1	1	1	1	1	1	1	1
1-Octanol	Alcohol	1	1	1	1	1	2	2	1	3	1	1	3	1
Phenol^{T}	Alcohol	1	1	1	2	2	4	4	4	6	3	3	4	3
Butylated hydroxytoluene	Alcohol	<1	<1	<1	<1	<1	<1	1	<1	<1	<1	<1	<1	<1
Ethylene glycol^{T}	Glycol	32	39	12	41	44	17	<1	<1	21	<1	44	21	21
1,2-Propanediol	Glycol	<1	12	4	<1	5	<1	<1	<1	<1	<1	4	3	<1
2-Butoxyethanol^{T}	Glycol	1	2	1	3	5	5	2	2	3	3	6	6	3
2-(2-Butoxyethoxy)ethanol^{T}	Glycol	2	<1	<1	2	<1	<1	2	<1	<1	2	<1	<1	<1
Hexanal	Aldehyde	8	20	8	10	19	12	26	22	17	25	25	16	18
2-Furancarboxaldehyde	Aldehyde	<1	1	1	1	2	2	2	2	2	1	2	2	2
Heptanal	Aldehyde	1	2	1	1	1	1	2	2	3	2	2	2	2
Benzaldehyde	Aldehyde	4	2	1	1	2	2	3	3	3	2	2	3	2
Octanal	Aldehyde	1	2	2	2	2	2	3	3	4	3	3	3	3
Nonanal	Aldehyde	2	2	2	2	3	3	3	3	4	4	3	4	3

Table 4, Continued. Concentrations (ppb) of individual VOCs in the four study houses on 9/16/97, 11/19/97 and 5/1/98.

		Concentration (ppb)												
	Chemical		PH2			PH18			PH19			PH20		Median
Compound	Class	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	Value
2-Butanone	Ketone	6	8	2	16	28	6	7	4	4	8	7	5	6
4-Methyl-2-pentanone	Ketone	<1	1	<1	<1	<1	<1	1	<1	<1	<1	<1	<1	<1
Cyclohexanone	Ketone	1	<1	<1	2	3	2	1	1	1	1	1	1	1
1-Phenylethanone[T]	Ketone	1	1	<1	1	<1	<1	1	1	<1	1	<1	<1	1
Acetic acid	Acid	25	102	142	80	122	264	123	120	267	53	126	275	122
Hexanoic acid	Acid	<1	1	2	1	2	3	1	1	6	<1	1	3	1
Ethyl acetate	Acetate	<1	1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Butyl acetate	Acetate	<1	1	<1	1	1	1	1	<1	<1	<1	<1	<1	<1
Texanol® 1 & 3	Ester	2	7	3	2	2	2	2	1	2	2	2	2	2
TXIB®	Ester	1	<1	<1	1	1	1	2	1	2	1	1	1	1
Benzothiazole	Misc	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
SigmaVOC		155	298	211	210	319	371	155	298	211	210	319	371	308
SigmaVOC (µg m-3)		662	1,120	662	739	1,140	1,170	1,530	1,220	1,490	896	1,190	1,280	1,150

[T] Toxic Air Contaminant (EPA, 1993).

*AromaHC = Aromatic hydrocarbon; AlkaneHC = Alkane hydrocarbon; CyclicHC = Cyclic hydrocarbon; TerpHC = Terpene hydrocarbon.

Table 5. The 18 most abundant VOCs in the four study houses. The ranges of the maximum concentrations (ppb) measured in the houses are shown.

Compound	Chemical Class	No. of Houses	Maximum Conc. Range ppb
Toluene	Aromatic HC*	1	6
n-Decane	Alkane HC	2	8 - 16
n-Undecane	Alkane HC	1	7
n-Dodecane	Alkane HC	2	5 - 10
n-Tridecane	Alkane HC	3	7 - 21
n-Tetradecane	Alkane HC	3	5 - 13
alpha-Pinene	Terpene HC	4	19 - 35
beta-Pinene	Terpene HC	4	6 - 11
3-Carene	Terpene HC	4	5 - 15
d-Limonene	Terpene HC	2	5 - 7
1-Butanol	Alcohol	1	6
Ethylene glycol	Glycol ether	4	21 - 44
1,2-Propanediol	Glycol ether	2	5 - 12
2-Butoxyethanol	Glycol ether	2	5 - 6
Hexanal	Aldehyde	4	19 - 26
2-Butanone	Ketone	4	7 - 28
Acetic acid	Acid	4	142 - 275
Texanol®	Ester	1	7

*HC = Hydrocarbon

Table 6. Concentrations and specific emission rates of TVOC, SigmaVOC, selected individual VOCs and formaldehyde in the two pre-study houses on 4/8/97.

	Concentration (ppb)		Emission Rate* ($\mu g\ m^{-2}\ h^{-1}$)	
Compound	**PH13-Pre**	**PH18-Pre**	**PH13-Pre**	**PH18-Pre**
n-Dodecane	2	8	24	46
n-Tridecane	8	17	84	103
n-Tetradecane	6	12	65	77
alpha-Pinene	20	25	156	113
beta-Pinene	4	9	35	43
3-Carene	4	14	33	66
d-Limonene	3	7	22	33
1-Butanol	4	8	12	14
Phenol	3	5	12	14
Ethylene glycol	18	30	65	63
Formaldehyde	39	65	62	63
Hexanal	10	20	57	69
Acetic acid	5	19	<6	27
SigmaVOC (ppb)	104	212	675	828
TVOC ($\mu g\ m^{-3}$)	641	1,090	867	880

*Ventilation rates in Houses PH13-Pre and PH18-Pre were 0.58 and 0.34 h^{-1}, respectively.

Table 7. Specific emission rates of individual VOCs in the four study houses on 9/16/97, 11/19/97 and 5/1/98.

		Specific Source Strength (μg m^{-2} h^{-1})												
	Chemical		PH2			PH18			PH19			PH20		Median
Compound	**Class***	**9/97**	**11/97**	**5/8**	**9/97**	**11/97**	**5/8**	**9/97**	**11/97**	**5/8**	**9/97**	**11/97**	**5/8**	**Value**
Benzene	AromaHC	1	<1	1	1	<1	1	1	<1	1	1	<1	<1	1
Toluene	AromaHC	<1	10	3	4	4	5	<1	<1	4	<1	4	4	4
Ethylbenzene	AromaHC	1	2	1	1	1	1	2	<1	<1	<1	<1	1	1
m/p-Xylene	AromaHC	7	8	3	3	<1	2	9	2	2	1	<1	4	3
Styrene	AromaHC	6	15	7	2	3	3	4	3	4	4	5	3	4
1,3,5-Trimethylbenzene	AromaHC	8	10	2	<1	<1	<1	2	<1	<1	<1	<1	<1	<1
1,2,4-Trimethylbenzene	AromaHC	24	32	8	3	<1	1	7	2	2	2	<1	1	2
Naphthalene	AromaHC	2	1	1	4	1	2	5	3	3	2	<1	<1	2
4-Phenylcyclohexene	AromaHC	1	<1	<1	2	<1	<1	1	<1	<1	1	<1	<1	<1
n-Heptane	AlkaneHC	1	5	2	6	1	3	16	13	14	4	3	6	4
n-Nonane	AlkaneHC	21	12	1	<1	3	<1	14	3	1	5	2	2	2
n-Decane	AlkaneHC	127	137	13	6	4	2	39	20	7	12	9	2	10
n-Undecane	AlkaneHC	58	76	25	3	2	1	15	9	6	6	4	1	6
n-Dodecane	AlkaneHC	8	11	8	19	19	21	62	49	36	33	35	17	20
n-Tridecane	AlkaneHC	5	13	11	75	61	62	135	110	74	82	95	46	68
n-Tetradecane	AlkaneHC	7	7	10	48	35	47	89	70	76	45	54	34	46
n-Pentadecane	AlkaneHC	5	5	6	5	4	5	5	4	5	4	5	4	5
n-Hexadecane	AlkaneHC	3	3	6	4	2	4	2	2	3	3	3	3	3
Methylcyclohexane	CyclicHC	<1	11	2	6	<1	1	2	<1	4	2	<1	7	2
Propylcyclohexane	CyclicHC	7	5	<1	<1	<1	<1	3	<1	<1	<1	<1	<1	<1
Butylcylohexane	CyclicHC	14	19	3	<1	<1	<1	4	2	1	1	1	<1	1

Table 7, Continued. Specific emission rates of individual VOCs in the four study houses on 9/16/97, 11/19/97 and 5/1/98.

Compound	Chemical Class*	Specific Source Strength ($\mu g\ m^{-2}\ h^{-1}$)												Median Value
		PH2			PH18			PH19			PH20			
		9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	
alpha-Pinene	TerpHC	99	171	57	84	189	75	166	157	73	119	169	41	109
Camphene	TerpHC	3	6	2	2	7	3	8	7	4	4	8	2	4
beta-Pinene	TerpHC	25	51	17	14	40	20	50	38	23	35	44	12	30
3-Carene	TerpHC	24	55	19	12	28	17	69	54	32	49	70	20	30
d-Limonene	TerpHC	11	25	13	10	19	15	31	25	19	24	36	13	19
1-Butanol	Alcohol	5	22	12	11	11	2	9	8	9	8	12	8	9
2-Ethyl-1-hexanol	Alcohol	5	19	7	9	5	7	6	4	5	4	7	5	5
1-Octanol	Alcohol	5	10	14	7	6	17	7	4	14	6	8	13	7
Phenol	Alcohol	2	7	3	14	9	17	13	14	16	11	15	12	13
Butylated hydroxytoluene	Alcohol	4	2	1	2	<1	<1	6	4	3	<1	<1	<1	1
Ethylene glycol	Glycol	56	162	60	179	122	55	<1	<1	46	<1	135	45	56
1,2-Propanediol	Glycol	<1	61	25	<1	16	<1	<1	<1	<1	<1	<1	<1	<1
2-Butoxyethanol	Glycol	3	14	10	22	24	29	9	10	12	15	33	24	15
2-(2-Butoxyethoxy)ethanol	Glycol	11	3	3	14	<1	3	7	<1	1	9	<1	1	3
Hexanal	Aldehyde	45	137	63	69	86	65	89	81	61	94	126	56	75
2-Furancarboxaldehyde	Aldehyde	<1	8	4	7	7	10	6	5	8	5	11	8	7
Heptanal	Aldehyde	4	13	10	5	7	9	7	7	10	7	11	8	8
Benzaldehyde	Aldehyde	19	14	<1	8	6	4	10	8	4	7	9	3	7
Octanal	Aldehyde	7	21	15	10	14	16	13	14	16	14	22	14	14
Nonanal	Aldehyde	3	21	19	12	18	23	11	14	18	13	23	17	18

Table 7, Continued. Specific emission rates of individual VOCs in the four study houses on 9/16/97, 11/19/97 and 5/1/98.

		Specific Source Strength (μg m^{-2} h^{-1})												
	Chemical		PH2			PH18			PH19			PH20		Median
Compound	Class	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	9/97	11/97	5/8	Value
2-Butanone	Ketone	21	36	12	80	90	22	15	10	9	20	23	11	20
4-Methyl-2-pentanone	Ketone	<1	10	<1	3	1	2	2	<1	1	<1	<1	<1	<1
Cyclohexanone	Ketone	5	<1	4	16	13	9	4	4	3	3	5	3	4
1-Phenylethanone	Ketone	4	2	<1	4	<1	<1	4	1	<1	2	1	<1	1
Acetic acid	Acid	52	408	632	298	328	808	237	258	546	100	378	563	353
Hexanoic acid	Acid	<1	8	14	2	8	18	4	4	22	1	7	14	7
Ethyl acetate	Acetate	<1	5	<1	<1	<1	1	1	<1	1	<1	<1	<1	<1
Butyl acetate	Acetate	2	11	<1	5	5	4	3	2	<1	<1	<1	<1	2
Texanol® 1 & 3	Ester	29	96	58	32	17	24	18	11	19	15	21	19	20
TXIB®	Ester	8	8	8	13	8	14	18	12	19	9	9	9	9
Benzothiazole	Misc	1	<1	<1	<1	1	<1	<1	<1	<1	<1	<1	<1	<1

*AromaHC = Aromatic hydrocarbon; AlkaneHC = Alkane hydrocarbon; CyclicHC = Cyclic hydrocarbon; TerpHC = Terpene hydrocarbon.

Table 8. Specific emission rates of selected VOCs and formaldehyde from a specimen of plywood floor sheeting measured at 24, 48 and 72 hours elapsed time in a small-scale environmental chamber.

Compound	Chemical Class	Emission Rate (µg m^{-2} h^{-1}) 24 h	48 h	72 h
alpha-Pinene	Terpene HC	233	143	63
beta-Pinene	Terpene HC	94	61	30
d-Limonene	Terpene HC	90	78	41
Formaldehyde	Aldehyde	48	31	29
Hexanal	Aldehyde	551	465	212
Heptanal	Aldehyde	24	20	11
Octanal	Aldehyde	53	41	24
Nonanal	Aldehyde	53	37	22
Acetic acid	Acid	751	469	340

Table 9. Comparison of concentrations (ppb) of selected oxidized organic compounds in the four study houses with their odor thresholds (Devos *et al.*, 1990).

Compound	Chemical Class	Odor Thres. (ppb)	Concentration Range (ppb) PH2	PH18	PH19	PH20
1-Octanol	Alcohol	6	1	1 - 2	1 - 3	1 - 3
Formaldehyde	Aldehyde	870	21 - 30	32 - 36	38 - 40	40 - 47
Hexanal	Aldehyde	14	8 - 20	10 - 19	17 - 26	16 - 25
Heptanal	Aldehyde	5	1 - 2	1	2 - 3	2
Octanal	Aldehyde	1	1 - 2	2	3 - 4	3
Nonanal	Aldehyde	<1	2	2 - 3	3 - 4	3 - 4
Acetic Acid	Acid	140	25 - 142	80 - 264	120 - 267	53 - 275
Hexanoic acid	Acid	13	<1 - 2	1 - 3	1 - 6	<1 - 3

Table 10. Comparison of concentrations (µg m^{-3}) of selected VOCs in the four study houses with concentrations typically measured in existing residences.

Compound	Summarized WAGM Conc.* (µg m^{-3})	Test Houses Conc. Range (µg m^{-3})	Test Houses Median Conc. (µg m^{-3})
Benzene	5 - <10	1 - 2	2
Toluene	20 - <50	4 - 21	9
Ethylbenzene	5 - <10	1 - 3	1
m/p-Xylene	10 - <20	2 - 12	3
Styrene	1 - <5	1 - 10	4
1,3,5-Trimethylbenzene	1 - <5	<1 - 7	1
1,2,4-Trimethylbenzene	5 - <10	1 - 22	3
Naphthalene	<1	1 - 5	2
n-Heptane	1 - <5	1 - 21	5
n-Nonane	1 - <5	1 - 18	3
n-Decane	5 - <10	3 - 93	9
n-Undecane	1 - <5	1 - 46	7
n-Dodecane	1 - <5	4 - 73	19
n-Tetradecane	1 - <5	5 - 105	39
n-Pentadecane	1 - <5	3 - 6	4
n-Hexadecane	<1	2 - 3	2
Methylcyclohexane	1 - <5	<1 - 8	2
alpha-Pinene	1 - <5	30 - 196	96
Camphene	10 - <20	1 - 9	4
beta-Pinene	<1	8 - 59	30
d-Limonene	20 - <50	6 - 37	17
1-Butanol	<1	1 - 14	9
2-Ethyl-1-hexanol	1 - <5	3 - 12	5
Hexanal	1 - <5	32 - 106	74
Nonanal	5 - <10	9 - 23	18
2-Butanone	1 - <5	7 - 83	18
4-Methyl-2-pentanone	<1	<1 - 6	1
Ethyl acetate	5 - <10	<1 - 3	<1
Butyl acetate	1 - <5	<1 - 7	2

*Range of weighted average, geometric mean, concentrations for established dwellings (Brown *et al.*, 1994).

Table 11. Indoor sources of selected VOCs based on chamber emission studies of latex paints and carpet and vinyl flooring materials (Hodgson, 1998).

Compound	Chemical Class	Identified Source
Styrene	Aromatic HC	Carpet with SBR* latex
Toluene	Aromatic HC	Sheet flooring adhesive
1,2,4-Trimethylbenzene	Aromatic HC	Sheet vinyl flooring
4-Phenylcyclohexene	Aromatic HC	Carpet with SBR latex
n-Decane	Alkane HC	Sheet vinyl flooring
n-Dodecane	Alkane HC	Sheet vinyl flooring
n-Tridecane	Alkane HC	Sheet vinyl flooring
n-Tetradecane	Alkane HC	Sheet vinyl flooring
Phenol	Alcohol	Sheet vinyl flooring
Butylated hydroxytoluene	Alcohol	Bonded urethane carpet cushion
Ethylene glycol	Glycol ether	Latex paint
1,2-Propanediol	Glycol ether	Latex paint
2-(2-Butoxyethoxy)ethanol	Glycol ether	Latex paint
Cyclohexanone	Ketone	Sheet vinyl seam sealer
Texanol®	Ester	Latex paint
TXIB®	Ester	Sheet vinyl flooring
Benzothiazole	Misc.	Rubber cove base

*SBR = Styrene-butadiene-rubber.

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