Implementation of Source Reduction Practices for Volatile Organic Compounds in Manufactured House Construction: Pilot Demonstration Project

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Abstract

Indoor air quality (IAQ) in new houses, particularly occupant's inhalation exposure to toxic, irritant and odorous chemicals, has received comparatively little attention among house builders and product manufacturers. The volatile organic compounds (VOCs) of potential concern in new houses include formaldehyde, acetaldehyde, acetic acid and naphthalene. These VOCs are emitted by a variety of wood products and other materials used to finish the interiors of most houses.

This study sought to demonstrate the efficacy of several low-cost measures intended to reduce the emissions and concentrations of formaldehyde and other VOCs in the production of a single manufactured house. The study was conducted as a collaborative effort with a nationwide producer of such houses. Two doublewide houses were selected for study. One received modifications to the cabinetry and countertop materials, a weatherization barrier under a low-emitting carpet system, and low VOC-impact interior paints. The other, produced at about the same time, did not have IAQ modifications and served as the control. The houses were installed on nearby lots in a sales center and were decorated for use as model homes. Samples for formaldehyde, acetaldehyde and other VOCs were collected in the houses at approximately three

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and six months after they were fully operational. Outdoor air ventilation rates also were measured.

The emission rates of higher molecular-weight aldehydes and terpene hydrocarbons predominantly associated with the plywood subfloor were reduced in the modified house likely due to the use of the weatherization barrier. The low-VOC paints substantially reduced the concentration of a major volatile component of interior wall paints. However, the concentrations and emissions of formaldehyde unexpectedly were higher in the modified house (e.g., the emission rate was a factor of two higher). The remainder of the study was spent diagnosing this difference. The heating and air conditioning system was eliminated as a possible source. Measurements of formaldehyde emissions from the particleboard components of the furnishings revealed that the new wood furniture purchased to decorate the modified house, but not the control house, was the likely source of the excess formaldehyde emissions. When approximately adjusted for the emissions from the new furniture, the formaldehyde emission rate in the modified house was nearly equivalent to rate in the control house. This emission rate resulted in formaldehyde concentrations below 50 ppb in the control house.

Key Words: ***Formaldehyde, Furniture, Indoor air quality, Manufactured house, Wood products***

Introduction

In 2003, the manufactured housing industry shipped 131,000 homes accounting for about eight percent of new single-family housing starts in the U.S. (MHI, 2004). Manufactured houses are built to Department of Housing and Urban Development (HUD) standards. The HUD Code is designed for compatibility with factory production and implements a thorough inspection process with the objective of assuring a high degree of safety and quality in the design and construction of these houses. Manufactured houses have an affordability advantage over traditional site-built houses because they benefit from large volume purchasing discounts and utilize cost-effective assembly line techniques. The net result is that good quality houses are produced at substantially lower costs per-square-foot relative to traditional houses. Continued improvements in the quality of manufactured houses may enhance their position in the marketplace.

Indoor air quality (IAQ), particularly occupant inhalation exposures to toxic, irritant and odorous chemicals, is an important aspect of house quality that has received comparatively little attention in either the manufactured or the traditional housing industry. Indoor exposures that occur as the result of emissions of gaseous pollutants from the materials and products that are used in the construction of houses may affect occupants' health and comfort as well as their overall satisfaction with their new homes. These emissions can be reduced by careful selection of the materials and products used to finish the interiors and likely by selected construction modifications. Implementation of these changes is particularly well suited to the central design and assembly line techniques employed by the manufactured house industry. The potential of this process to achieve low airborne concentrations of volatile organic compounds (VOCs) of potential health and comfort concern in manufactured buildings was demonstrated recently in the industrialized school classroom industry (Hodgson *et al*., 2004).

In this report, we provide background information on the classification of VOCs of most concern in new houses and on the results of our previous studies to identify and control the sources of these compounds in a new manufactured house and in school classrooms. We describe the design of the current pilot demonstration project and the methods employed. The concentrations and emission rates of VOCs measured in a modified study house and matched control house are discussed relative to the objective of demonstrating measures for reducing the potential inhalation exposures of occupants to formaldehyde and other VOCs.

VOCs of Concern

There have been two limited, cross-sectional studies of VOC concentrations in new residences in recent years (Lindstrom *et al*., 1995; Hodgson *et al*., 2000). In one study, concentrations were measured in four new, high-quality, manufactured houses over 2-9 months following installation and in seven new site-built houses 1-2 months after completion (Hodgson *et al*., 2000). The predominant VOCs were terpene hydrocarbons, formaldehyde, other aldehydes and acetic acid. The predominant sources of these compounds are wood-based products (Hodgson *et al*., 2002b). In general, VOC concentrations and emission rates were similar in both housing types, likely reflecting the similarity in interior finish materials. The concentrations of VOCs measured in North American office buildings and houses since 1990 have been reviewed by Hodgson and Levin (2003a). Included was a comparison of VOC concentrations in the above-cited studies of new houses with concentrations measured in existing dwellings not selected with respect to age.

In general, the concentrations of aldehydes (excluding formaldehyde) and various hydrocarbons were higher in the new houses.

The concentrations reported in office buildings and houses have been classified with respect to their potential to cause noncancer chronic toxicity, sensory irritation of the eyes and upper respiratory tract, and odor response (Hodgson and Levin, 2003b). Sensory irritation levels relevant for the general population were derived from animal and human studies and from occupational guidelines. Guidance levels established by governmental agencies were emphasized in selecting appropriate exposure levels for chronic toxicants (California EPA, 2003; ASTDR, 2003; U.S. EPA, IRIS). Hazard quotients were individually calculated for noncancer chronic effects by dividing maximum or derived 95th percentile VOC concentrations by the guidance levels. This analysis revealed that only a few compounds are likely to be of primary concern with respect to serious chronic health effects. Of these, formaldehyde, acetaldehyde, naphthalene, and tetrachloroethene are known to be emitted by some common building materials and products used in houses. Measured concentrations also were compared with odor thresholds (Devos *et al*., 1990). For new residences, higher molecular weight aldehydes, acetic acid, and hexanoic acid were shown to be potential sources of noticeable odors (Hodgson and Levin, 2003b). On the other hand, very few compounds occur at concentrations sufficiently high to produce sensory irritation. Two notable exceptions associated with wood-based product emissions in new and existing residences are formaldehyde and acetic acid (*ibid*.).

Identification and Control of VOC Sources

A detailed study was conducted to identify the major sources of formaldehyde, less volatile aldehydes and terpene hydrocarbons in a new, high-quality, manufactured house (Hodgson *et al*, 2002b). Materials used to construct the interior of the house were collected from the production facility. Wood-based products were emphasized. Specimens of the materials were tested in small-scale environmental chambers for emissions of formaldehyde and other VOCs. Measurements were made after a 3-week exposure, and area-specific emission rates (*i.e*., emission factors) were calculated. Whole-house emission rates for combined materials were predicted based on the emission factors and the corresponding material quantities. These predicted values were compared to whole-house emission rates derived from measurements of VOC concentrations and ventilation rate made at the house three months after its installation. For 10 of the 14 target compounds, including formaldehyde, the predicted and derived rates were

within a factor of two of each other, which considering the uncertainties involved, is reasonably good agreement. The predominant sources of formaldehyde in the house were bare particleboard (PB) and medium density fiberboard (MDF) surfaces in the cabinetry casework and molded high-density fiberboard doors. The plywood subfloor under the carpet was a smaller source of formaldehyde and the major source of higher molecular weight aldehydes and terpene hydrocarbons.

As the result of this study, recommendations were developed for reducing concentrations of formaldehyde and other VOCs in newly constructed houses (Hodgson *et al*., 2002a). These are reproduced here in Table 1. The first five recommendations are aimed at controlling or eliminating important sources of formaldehyde. Other potential sources of formaldehyde not addressed in the house study or in the table include tack strips used for the installation of wall-to-wall carpet and fiberglass insulation used in wall, floor and ceiling cavities. Use of barrier materials on the floor (Recommendation No. 6) may result in moisture condensation problems in hot-humid climates and possibly other situations and, therefore, should be selected and used with caution.

Introduction of VOC Source Control Practices into Factory Production

Laboratory-based material testing combined with modeling and field validation to select low VOC-impact interior finish materials can help building manufacturers produce structures with acceptable IAQ. This process was recently demonstrated for factory produced school classrooms (Hodgson *et al*., 2001, 2002a and 2004). The study involved the participation of a large California manufacturer of conventional relocatable classrooms (RCs) and two Northern California school districts. The study was conducted in two stages with both laboratory- and field-based components. The laboratory study objectives were to characterize the emissions of VOCs both from standard materials used to finish the interiors of this manufacturer's RCs and from alternate, cost-competitive materials with potentially lower impacts on VOC concentrations (Hodgson *et al*., 2001). Based on the results of the laboratory study, several alternate materials were selected that had the potential to reduce classroom concentrations of VOCs of concern. Specifications then were developed for four new RCs. Two were designed with standard interior finishes, and two were designed to incorporate the alternate materials. The classrooms were constructed and installed in pairs at elementary schools in the participating school districts. During the subsequent two semesters, school-day integrated indoor and outdoor VOC

concentrations were measured weekly and experiments were conducted to derive whole-building VOC emission rates.

Both the standard and alternate materials used to construct the interiors of these RCs generally were shown to be low sources of toxic and odorous VOCs. Nevertheless, in approximately one third of the compared cases, VOC ERs and concentrations in the RCs were predicted with reasonable accuracy, *i.e.*, within a factor of two, based on the results of the laboratory study of material emissions. In addition, statistically significant differences in mean concentrations between modified and standard RCs were observed for five VOCs of concern with the lowest concentrations occurring in the modified classrooms (Hodgson *et al*., 2004).

Study Objectives

The objective of this study was to implement and demonstrate relatively low-cost, existing technologies to reduce the sources of formaldehyde and other VOCs of concern in the production of a single manufactured house.

Methods

Study Design

This pilot demonstration project was a collaborative effort among the Florida Solar Energy Center (FSEC), Lawrence Berkeley National Laboratory (LBNL), and Palm Harbor Homes, Inc. (PHH), a leading nationwide producer of high-quality, multi-section, manufactured houses with corporate offices in Addison, TX. The project was conducted at PHH's production facility and sales office in Plant City, FL. The project was originally conceived in 2002 as a side-by-side demonstration of simultaneous improvements in energy performance and IAQ to be achieved using existing technologies. The concept was to build two houses, essentially identical with respect to their size, floor plan and major materials. One house would have added features to improve energy performance and IAQ. The other house would have no special modifications and would serve as the control. They would be sited in a residential community on adjacent, identical lots. Both would have computer-simulated occupancy (*i.e.*, controlled use of lights, appliances, water use, heating, and cooling). Monitoring of energy usage and performance and IAQ metrics would be conducted over a one-year period. Unfortunately, the project participants were unable to find an appropriate residential site and obtain commitments for the funds needed to maintain the houses at the site for a year. Consequently, the study plan was modified in 2003

to substantially reduce the costs and to take advantage of PHH's model home sales office in Plant City.

Approximately on an annual cycle, PHH builds examples of their new houses for display at their sales office. The houses present PHH's range of models and features. They are decorated and furnished, but unoccupied. The houses are open to the public during normal business hours seven days a week and their heating and cooling systems are operated accordingly. Although the situation was convenient, we recognized from the beginning that there were limitations to the use of these houses as study houses. The houses generally vary somewhat with respect to size and floor plan, interior finishes and furnishings, and orientation with respect to sun and wind. Monitoring instrumentation must be minimized and kept out of sight, and sampling can only be conducted outside of normal business hours. Computer controlled simulation of occupancy, a key feature of the original design, is not possible. To the limited extent possible, the study plan was revised to accommodate these factors.

In June 2003, two model houses, then in the planning stage, were selected for use in the project. A 1,440-ft^2, doublewide house, designated as the "Study" house, was selected to receive the energy and IAQ modifications. A 1,540-ft^2 doublewide house, designated as the "Control" house, was selected to serve as the primary control house. The houses were to be installed on nearby lots in the sales center in approximately the same orientation with respect to the sun.

The project participants early on developed specifications for enhanced IAQ. These specifications were reviewed and revised in June 2003 to reflect those energy and IAQ modifications determined by PHH management to be relatively easily installed on the production line and/or during installation of the houses at the site. The revised IAQ specifications for the Study house are listed in Table 2. The weatherization membrane (Tyvek®, Dupont) was selected as an appropriate barrier material for the floor because it is water vapor permeable and is designed to help prevent mold growth. The interior latex paints (Harmony® brand, Sherwin-Williams) contain no VOCs as determined by EPA method 24.

Field and Laboratory Methods

The field and laboratory methods for the project were adopted from previous studies conducted together by FSEC and LBNL (Hodgson *et al*., 2000 and 2002). Active sampling for VOC air contaminants was performed in the houses at the end of the day after the model center was closed. To accommodate the energy-related portion of the study, model center staff were

instructed to always leave on the heating and air conditioning systems. House air change rates were measured concurrently with the collection of air samples to allow the derivation of whole-house emission rates and emission factors. Prior to initiation of sampling, a tracer gas, sulfur hexafluoride (SF_6), was introduced throughout a house. SF_6 concentrations in air at a central location were measured on a ten-minute cycle with a photoacoustic infrared analyzer (Model 1302, Brüel & Kjær Instruments, Denmark). After sufficient time for mixing, the outdoor air 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.

At each sampling event, integrated air samples for VOCs and aldehydes were collected over three hours inside each house and outdoors. Active sampling systems consisted of timer-controlled peristaltic pumps (L/S® Fixed-Speed Drive, Cole-Parmer Instr. Co.). These were used to obtain duplicate VOC samples and a single aldehyde sample at each location. VOC gas samples are collected onto Tenax®-TA sorbent tubes (CP-16251, Varian Inc.) modified by substituting a 15-mm section of Carbosieve S-III 60/80 mesh (10184, Supelco Inc.) at the outlet end. Aldehyde samples were collected on treated, 2,4-dinitrophenylhydrazine (DNPH), silica-gel cartridges (WAT047205, Waters Corp.). The sampling media were positioned in a single central area inside each house at about 1.5 m above the floor and at least 0.5 m away from walls and other surfaces. Samples were collected outdoors from a single central location. Flow rates of the sampling systems, ~5-6 $cm^3\ min^{-1}$ for VOCs and ~150 $cm^3\ min^{-1}$ for aldehydes, were measured near the beginning and end of each sampling interval. Field blanks also were collected for each sampling event.

Passive monitors were used to obtain longer-term integrated air samples for formaldehyde. The aldehyde monitors (N571, Assay Technology) were deployed for approximately one-week intervals at a single central location in each house. These monitors are based on the same DNPH chemistry as used in the active sampling cartridges.

The VOC samples were analyzed for 32 target compounds by thermal desorption-gas chromatography/mass spectrometry (TD-GC/MS) generally following U.S. EPA Method TO-1 (U.S. EPA, 1984). A field blank and at least one duplicate sample were analyzed with each batch of samples. Both active and passive aldehyde samples were extracted and analyzed for formaldehyde and acetaldehyde by high performance liquid chromatography with UV detection following ASTM standard method D-5197-97 (ASTM, 1997b).

Data analysis

The Study and Control houses were compared over time with respect to their measured indoor concentrations of selected VOCs and their derived whole-house emission rates (ERs) for these target compounds. ERs in mass per time (mg h^{-1}) were determined assuming the houses were ideal continuously-stirred, tank reactors (CSTRs) operating at near steady-state conditions (ASTM, 1997a). Any net losses of emitted VOCs onto non-source materials are implicitly included. Thus, net effective ERs are calculated. The steady-state form of the mass-balance model for CSTRs was used:

$$ER = Va\,(C - C_0) \tag{1}$$

where V is the ventilated volume (m^3) determined as 95% of the floor area times the average ceiling height; a is the outdoor air ventilation or air change rate (h^{-1}); C is the indoor air concentration of the compound ($\mu g\ m^{-3}$); and C_0 is the outdoor air concentration of the compound ($\mu g\ m^{-3}$).

Area-specific emission rates or emission factors (EFs) in mass per area-time ($\mu g\ m^{-2}\ h^{-1}$) were calculated as:

$$EF = \frac{Q\ (C - C_O)}{A} \tag{2}$$

where A (m^2) is the total floor area.

Results and Discussion

The two houses were produced in late July and early August 2003. Installation of the two houses was completed and the heating and air conditioning (HAC) systems were operational by the end of September. The originally planned IAQ modifications to be installed in the Study house are listed in Table 2. As footnoted in the table, not all of these modifications were made. Standard molded, high-density fiberboard, passage doors were used, as the door manufacturer no longer produces vinyl-coated doors. Medium-density fiberboard (MDF) was used for the face frames of the cabinets because PHH did not have sufficient stock of the plywood material. Standard tack strips with unquantified emissions of formaldehyde were used for the carpet installation, as LBNL was unable to identify an alternate with low formaldehyde emissions. This latter source

potentially is significant despite the relatively small quantity of material. For example, a commonly available brand of tack strip obtained from a retail outlet in Emeryville, CA emitted 17 $\mu g\ m^{-1}\ h^{-1}$ of formaldehyde after 14 days exposure in an environmental chamber. This product could contribute as much as 0.5 $mg\ h^{-1}$ to the whole-house formaldehyde emission rate based on the quantity used.

The initial set of active air samples for VOCs and aldehydes was collected outdoors and in the Study and Control houses on December 11, 2003, approximately 2.5 months after the houses were fully operational. The second set of active samples was collected three months later on March 2, 2004. Passive aldehyde samples were obtained in the Study and Control houses and in an additional triple-wide house of approximately the same age over four one-week intervals between these dates.

Adjusted VOC and aldehyde concentrations were calculated as an indoor concentration minus its respective outdoor concentration. These data for 24 target compounds in the two houses on the December and March sampling dates are presented in Table 3. Compounds with low concentrations (*i.e.*, generally <5 $\mu g\ m^{-3}$) were omitted. The compounds are listed here and in a subsequent table by chemical class (*i.e.*, acids, aldehydes, ketones, alcohols, esters, aromatic hydrocarbons, and terpene hydrocarbons) and then in order of decreasing volatility within each class.

Compounds with at least one measured concentration in excess of 100 $\mu g\ m^{-3}$ were acetic acid, formaldehyde, hexanal, 2-propanone (acetone), 2-butoxyethanol, and α-pinene. The concentrations of many of the aldehydes (*i.e.*, acetaldehyde, pentanal, hexanal, heptanal, and octanal) and terpene hydrocarbons (*i.e.*, α-pinene, β-pinene, and 3-carene) were relatively consistent between the two houses and the two sampling dates.

There were, however, some distinct differences between the concentrations measured in the two houses. Notably, the concentrations of formaldehyde in the Study house were about three times higher than concentrations in the Control house. This difference was not anticipated based on the source reduction measures aimed at lowering the emissions of formaldehyde in the Study house. 2-Propanone concentrations were two-fold lower in the Study house, although there is no obvious connection to the source reduction measures. On the other hand, 2-butanone (methyl ethyl ketone) concentrations were about an order of magnitude higher in the Study house. The

source of this compound in this house also is not known. The concentrations of the combined isomers of 2,2,4-trimethyl-1,3-pentanediol monoisobutyrate (TMPD-MIB) and toluene were substantially lower in the Study house. TMPD-MID is a coalescing aid used in latex paints and the difference likely can be attributed to the use of low-VOC paints in the Study house. Toluene is used in some adhesives (Hodgson, 1999) and possibly in some oil-based paints. The concentration of 2-butoxyethanol was elevated in both houses in March, and the concentration of d-limonene was elevated in the Control house in March. These two compounds may have been associated with cleaning activities since they are present in many consumer products such as glass cleaners and general purpose cleaning solutions (Nazaroff and Weschler, 2004).

Indoor formaldehyde concentrations measured by passive sampler are shown in Table 4. These values are not corrected for outdoor concentrations. The values for the Study and Control houses are in good agreement with the results for active samples collected over short time intervals (Table 3) and confirm the factor of two to almost four differences in formaldehyde concentrations between the two houses. The formaldehyde concentrations for the triple-wide house lie between the values for the Study and Control houses.

On the December 2003 sampling date, the air change rates measured by tracer gas decay in the Study and Control houses were 0.22 and 0.36 h^{-1}, respectively. The air change rates, the estimated ventilated volumes and the adjusted VOC concentrations were use to derive whole house emission rates and emission factors (Table 5). These results show that the formaldehyde generation rate in the Study house was about twice the generation rate in the control house while the acetaldehyde generation rates were nearly equal. The plywood subfloor in the carpeted areas is believed to be a predominant source of the higher molecular weight aldehydes (*i.e.*, pentanal through nonanal) and the terpene hydrocarbons based on detailed laboratory and field measurements of a similar house (Hodgson *et al*., 2002b). The emission rates and emission factors of these compounds consistently were lower in the Study house by a factor of about 0.4 to 0.6. These results are generally consistent with the reductions in the emissions of these compounds from plywood observed in the laboratory when the same brand of weatherization membrane was placed over the surface (*ibid*.). Thus, it is likely that the use of this membrane under the carpet system served to keep the concentrations of higher molecular weight aldehydes and terpene hydrocarbons in the Study house nearly equivalent to the respective concentrations in the Control house despite the lower ventilation rate in the Study house.

On the March 2004 sampling date, the air change rates measured by tracer gas decay in the Study and Control houses were 0.10 and 0.11 h^{-1}, respectively. Due to the weather conditions on that day, it is likely that the HAC systems were on and the houses were operating at higher air change rates shortly before initiation of sampling. Since this assumed interval was short relative to the time needed to achieve steady state conditions, the March 2004 data could not be used for the derivation of emission rates and emission factors.

Based on previous laboratory measurements of formaldehyde emissions from interior components, we anticipated a minimum 25% reduction in the formaldehyde emission rate in the Study house relative to the Control house due to the use of fully encapsulated particleboard for the cabinetry casework, a diffusion barrier on the undersurface of the particleboard countertops, and the weatherization barrier applied over the plywood subfloor (Hodgson *et al*., 2002b). We additionally expected the difference to persist over the course of a year. The two-fold higher formaldehyde emissions in the Study house prompted us to abandon our original plan of quarterly measurements and instead to focus on identifying the unexpected source of formaldehyde emissions in this house. Firstly, FSEC and PHH staff jointly inspected the houses. This inspection confirmed that the intended formaldehyde source reduction measures had been implemented in the Study house. Two other potentially relevant differences between the houses were known at the time. Due to the energy efficiency specifications for the Study house, the HAC mechanical system in the house was produced by a different manufacturer than the HAC system in the Control house. Secondly, some furniture believed to be solid wood had been newly purchased for decoration of the Study house. Older furniture taken from PHH's stock was used to decorate the Control house.

In July 2004, we investigated the potential for the HAC systems to emit formaldehyde. Each system is located in a closet near the central living area. Active sampling for formaldehyde was conducted in each house with samplers placed at the HAC system return grill and inserted directly into the supply plenum of the HAC system. The system was operated and the samples were simultaneously collected over three hours. The results are shown in Table 6. The differences between the return and supply measurements were small, about plus 3% for the study house and about minus 8% for the control house. These differences are within the uncertainties of the measurements and, therefore, are not significant.

Another inspection revealed that some of the backsides and undersurfaces of the new wood furniture were fabricated from particleboard, a typically high formaldehyde emission source (Kelly *et al*., 1999; Hodgson *et al*., 2002b). Our first plan to investigate the impact of the new furniture on the formaldehyde concentrations and emissions in the Study house was to measure the formaldehyde concentration and the house air change rate, remove the furniture for at least four days, and repeat the formaldehyde and air change rate measurements at this condition. However, since the house was being used as a sales model, coordination of this move proved difficult and there were numerous delays. While waiting for an opportunity to move the furniture, the study was interrupted by weather conditions (*i.e*., hurricanes) and then effectively was terminated when the house was removed from the sales center.

In December 2004, approximately 14 months after the furniture was first delivered, we located the pieces in a storage garage. From one accessible piece, we obtained 4.4-cm diameter specimens of 3-mm thick particleboard using a hole-saw. Specimens of 13-mm thick particleboard were similarly collected from a furniture piece that was several years old and was used in the sunroom of the house.

The emissions of formaldehyde from the two specimens of furniture particleboard individually were measured in the laboratory using small-scale environmental chambers as described by Hodgson *et al*. (2002b). The exposure time was 24 h. Active samples for formaldehyde were collected at the chamber exhaust and analyzed as described above. Formaldehyde emission rates and emission factors were calculated using Equations 1 and 2. The emission factor results are presented in Table 7.

From the purchase requisition and the furniture manufacturer's sales literature, we determined there were eight new pieces of living room and master bedroom/retreat furniture that likely contained some particleboard. The total exposed surface area (one side) of particleboard in these pieces was estimated to be 8.5 m^2. Thus, the estimated formaldehyde emission rate attributable to the new furniture was 6.4 mg h^{-1}, which is about 80% of the total formaldehyde emission rate derived for the house in December 2003 (Table 5). Based on the formaldehyde emissions from the particleboard from the older furniture, it is likely that the formaldehyde emissions attributable to furniture would have been substantially lower if older furniture pieces had been used.

Conclusions

The introduction of new furniture into the Study House interfered with the evaluation of the low-cost measures intended to reduce sources of formaldehyde in the house. If one-half the estimated formaldehyde emission rate from the new furniture (*i.e.*, approximately the difference between the emissions from new and old furniture particleboard) is subtracted from the whole-house emission rate, the formaldehyde emission rate in the Study house is nearly equivalent to the rate in the Control house. This low rate (about 4.5 mg h^{-1}), which includes a furniture component, resulted in concentrations in the Control house of 24 to 51 μg m^{-3} or 20 to 42 ppb. A formaldehyde concentration of 50 ppb and below has been suggested as a reasonable target for new houses (Sherman and Hodgson, 2004). However, more recently, the State of California has recommended a lower value of 27 ppb to avoid irritant effects (California Air Resources Board, 2004). The source reduction measures directed toward other VOC sources were successfully demonstrated. The use of the weatherization barrier applied over the plywood subfloor in the Study house appeared to function as predicted to reduce the emissions of higher molecular weight aldehydes and terpene hydrocarbons from this source, and the use of the low VOC interior paint reduced the emissions of a major VOC component associated with latex paints.

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Table 1. Recommended VOC source reduction practices for new house construction

No.	Source Reduction Practice
1	When alternates exist, avoid wood products with urea-formaldehyde resin system
2	Construct cabinet cases with fully encapsulated wood products
3	Use frameless cabinets to eliminate MDF stiles
4	Apply laminate backing sheet to undersides of PB countertops
5	Use low-formaldehyde emitting passage doors
6	Apply barrier material over plywood subfloor in carpeted areas

Table 2. Revised indoor air quality specifications for Study house

Component	Specification
Cabinet Construction	Use plywood face frame material* and vinyl-two-sides (V2S) particleboard for all casework
Countertops	Construct all countertops with V1S particleboard with vinyl surface on underside of tops
Carpeted Floors	Install Tyvek® (Dupont) house wrap over plywood subfloor before installing carpet. Use Nylon 6,6 carpet and synthetic fiber carpet cushion (both CRI Green Label). Use carpet tack strips with low formaldehyde emissions*
Wall & Ceiling Paint	Use low VOC interior paints (Harmony® brand, Sherwin-Williams)
Passage Doors	Use vinyl-coated interior doors*
Trim	Use wood lumber trim throughout house, avoiding use of MDF
Recessed Light Fixtures	Install gasketed light fixtures

*MDF was used as face-frame material; standard carpet tack strips were used; standard un-coated interior doors were used.

Table 3. Adjusted (indoor minus outdoor) concentrations of selected VOCs measured by active sampling in Study and Control houses on December 11, 2003 and March 2, 2004

		Adjusted Concentration (μg m^{-3})			
	Chem	Study House		Control House	
Compound	Class	12/11/03	3/2/04	12/11/03	3/2/04
Acetic acid	Acid	880	350	670	390
Formaldehyde	Aldehyde	109	105	35	28
Acetaldehyde	Aldehyde	25	32	16.0	26
Pentanal	Aldehyde	46	63	45	45
Hexanal	Aldehyde	210	280	220	210
2-Furaldehyde	Aldehyde	4.6	7.1	3.6	2.4
Heptanal	Aldehyde	11.4	13.8	10.7	9.4
Octanal	Aldehyde	18.2	25	19.0	19.9
Nonanal	Aldehyde	12.7	34	14.9	18.7
2-Propanone	Ketone	65	82	111	195
2-Butanone	Ketone	51	62	5.5	8.3
4-Methyl-2-pentanone	Ketone	11.9	13.0	15.4	11.4
1-Pentanol	Alcohol	27	28	23	16.3
2-Butoxyethanol	Alcohol	17.6	53	6.3	108
TMPD-MIB*	Ester	1.3	3.1	35	19.1
Toluene	Aromatic	3.2	12.8	74	20
m/p-Xylene	Aromatic	2.1	3.3	1.5	5.4
Styrene	Aromatic	6.7	6.9	4.7	4.8
α-Pinene	Terpene	196	230	196	210
Camphene	Terpene	4.5	5.1	8.5	3.9
β-Pinene	Terpene	37	41	47	43
3-Carene	Terpene	15.3	21	17.1	15.0
d-Limonene	Terpene	17.8	22	25	67
p-Cymene	Terpene	5.7	6.2	8.0	3.9

*TMPD-MIB = 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (combined isomers)

Table 4. Concentrations of formaldehyde measured by passive sampling in Study, Control, and triple-wide houses on four weeks between December 2003 and March 2004

	Concentration ($\mu g\ m^{-3}$)		
Deployment Dates	Study House	Control House	Triple-Wide House
12/3/03 – 12/11/03	102	40	77
12/11/03 – 12/19/03	111	51	81
2/17/04 – 2/24/04	94	24	69
2/24/04 – 3/2/04	85	26	70

Table 5. Emission rates and emission factors for selected VOCs derived for Study and Control houses from VOC and ventilation rate measurements made on December 11, 2003. Study and Control houses had ventilated volumes were 330 and 351 m^3, respectively, and were operating at air change rates of 0.22 and 0.36 h^{-1}, respectively

Compound	Chem Class	Emission Rate (mg h^{-1}) Study House	Emission Rate (mg h^{-1}) Control House	Emission Factor (μg m^{-2} h^{-1}) Study House	Emission Factor (μg m^{-2} h^{-1}) Control House
Acetic acid	Acid	64	84	480	580
Formaldehyde	Aldehyde	8.0	4.4	60	31
Acetaldehyde	Aldehyde	1.83	2.0	13.7	14.0
Pentanal	Aldehyde	3.4	5.6	25	39
Hexanal	Aldehyde	15.5	28	116	195
2-Furaldehyde	Aldehyde	0.34	0.45	2.5	3.1
Heptanal	Aldehyde	0.83	1.33	6.2	9.3
Octanal	Aldehyde	1.34	2.4	10.0	16.6
Nonanal	Aldehyde	0.93	1.86	6.9	13.0
2-Propanone	Ketone	4.7	13.9	35	97
2-Butanone	Ketone	3.7	0.69	28	4.8
4-Methyl-2-pentanone	Ketone	0.87	1.92	6.5	13.4
1-Pentanol	Alcohol	2.0	2.9	15.0	20
2-Butoxyethanol	Alcohol	1.29	0.79	9.6	5.5
TMPD-MIB*	Ester	0.09	4.3	0.7	30
Toluene	Aromatic	0.23	9.3	1.7	65
m/p-Xylene	Aromatic	0.16	0.18	1.2	1.3
Styrene	Aromatic	0.49	0.59	3.6	4.1
α-Pinene	Terpene	14.4	24	107	171
Camphene	Terpene	0.33	1.06	2.4	7.4
β-Pinene	Terpene	2.7	5.8	20	41
3-Carene	Terpene	1.12	2.1	8.4	14.9
d-Limonene	Terpene	1.30	3.2	9.7	22
p-Cymene	Terpene	0.41	0.99	3.1	6.9

*TMPD-MIB = 2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (combined isomers)

Table 6. Concentrations of formaldehyde measured at heating and air conditioning (HAC) system return and supply registers of Study and Control houses in July 2004

House	Concentration ($\mu g\ m^{-3}$) HAC Return	HAC Supply	Difference	HAC System Condition
Study House	45.6	47.3	1.6	Heater on
Control House	31.0	28.7	-2.3	Heater off

Table 7. Formaldehyde emission factors (EFs) measured for samples of particleboard collected in December 2004 from new and aged wood furniture installed in Study house. Formaldehyde concentrations in the Study house as the result of the emissions from new furniture were predicted based on the estimated quantity of particleboard for the new furniture and the house outdoor airflow rates measured in December 2003

Particleboard Source	EF ($\mu g\ m^{-2}\ h^{-1}$)	ER[a] ($mg\ h^{-1}$)	Airflow Rate ($m^3\ h^{-1}$)	Predict Conc ($\mu g\ m^{-3}$)
New Furniture	750	6.4	73[b]	87
Aged Furniture	390	--	--	--

a. Emission rate (ER) was estimated assuming 8.5 m^2 of particleboard was used to cover backs and undersides of eight furniture pieces

b. Outdoor airflow rate for Study house on 12/11/03