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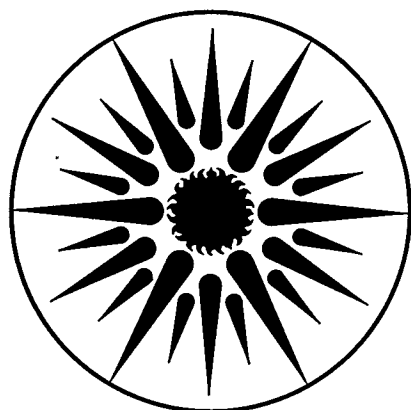
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**Measurement of Indoor Air Quality  
in Two New Test Houses**

A.T. Hodgson

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## Measurement of Indoor Air Quality in Two New Test Houses

Alfred T. Hodgson

Energy and Environment Division  
Ernest Orlando Lawrence Berkeley National Laboratory  
University of California  
Berkeley, California 94720

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**ABSTRACT** - This study was undertaken to assess indoor air quality in two similar, new houses being evaluated for energy performance. One house (A) was built conventionally. The other (B) was an energy-efficient structure. Air samples for individual volatile organic compounds (VOCs), total VOCs (TVOC) and formaldehyde were collected following completion of the interiors of the houses and on several occasions during the following year. Ventilation rates were also determined so that source strengths of airborne contaminants could be estimated with a mass-balance model.

There were no substantial differences in indoor air quality between the houses. The TVOC concentrations in House A ranged from 1,700 - 4,400  $\mu\text{g m}^{-3}$ , with the highest value coinciding with the lowest ventilation rate. The TVOC concentrations in House B were 2,400 - 2,800  $\mu\text{g m}^{-3}$ . These values are elevated compared to a median value of 700  $\mu\text{g m}^{-3}$  measured for a large residential study. Formaldehyde concentrations ranged up to 74  $\mu\text{g m}^{-3}$ . The dominant VOC in both houses was hexanal, an odorous chemical irritant. The concentrations of acetone, pentanal, toluene, alpha-pinene and other aldehydes were also relatively high in both houses.

The source strengths of many of the analytes did not decline substantially over the course of the study. For example, the initial TVOC source strength for House A was 385  $\text{mg h}^{-1}$ . Eight months later it was still 230  $\text{mg h}^{-1}$ . Interestingly, the source strengths of pentanal and hexanal increased over this period in House A. In House B, the source strengths of all VOCs declined over a one-year period. However, for a number of compounds, the decline was less than 50 percent.

A chamber study of oriented strand board (OSB) collected from House B found that this material emitted formaldehyde, acetone, hexanal and a few other VOCs also detected in the houses. Based on the chamber data, the OSB was estimated to contribute substantially to concentrations of formaldehyde and acetone in the houses. The results also suggested that OSB was not the dominant source of pentanal, hexanal and alpha-pinene, all of which had elevated emissions in the houses, possibly from a single source.

## INTRODUCTION

Good indoor air quality significantly contributes to the suitability and marketability of houses. Good indoor air quality can be achieved in new houses by providing adequate ventilation and by carefully managing the indoor sources of air contaminants. This study was undertaken to measure the air quality in two new houses that were being assessed for their energy performance. Both houses were the same floor plan with 3,350  $\text{ft}^2$  (311  $\text{m}^2$ ) of conditioned living space. House A was built conventionally, whereas, House B was a more energy-efficient structure that

incorporated several construction innovations, as well as some different materials. The potential impacts, if any, of these different construction methods and materials on indoor air quality were unknown. The houses were constructed near Pittsburgh, PA, by Integrated Building and Construction Solutions (IBACOS), Inc. IBACOS is a participant in the U.S. Department of Energy's Building America Program which has the objective of advancing comfort and energy efficiency in new housing through systems engineering approaches.

The design of the study was to collect indoor air samples for the analysis of individual volatile organic compounds (VOCs), total VOCs (TVOC) and formaldehyde shortly after completion of the houses and on several occasions during the following year. These samples were intended to be collected coincidentally with the determination of ventilation rates in the houses, although this requirement was not strictly adhered to. Measured or approximated ventilation rates were used in a simple mass-balance model to estimate the source strengths of the airborne organic contaminants. The use of source strengths allows comparisons of contaminant emissions to be made among sampling periods even if ventilation conditions vary. In this way, it is possible to determine the temporal profiles of emissions as the building and interior finish materials age and as new materials are introduced into the building. The study was initiated in November, 1993, shortly after the interior of House A was completed. Samples were collected in House A on three occasions between November, 1993, and July, 1994. A set of samples was collected in House B in July, 1994, shortly after its interior was completed and again in July and August, 1995. Both houses were unfurnished and unoccupied throughout the study.

## **METHODS**

### **Sampling and Analyses of Individual VOCs and TVOC**

The multisorbent samplers (Model ST-032, Envirochem, Inc.) used to collect the samples for VOCs and TVOC contained Tenax-TA, Amborsorb XE-340 and activated carbon, in series (Hodgson and Girman, 1989). With these samplers, C<sub>5</sub> to C<sub>16</sub> nonpolar and moderately polar compounds, and many C<sub>1</sub> to C<sub>4</sub> compounds, depending upon functional group, are quantitatively collected. Samples were generally collected indoors on all three levels of each house. Samples were also collected outdoors near the houses to provide background concentrations. Paired samples were collected at each sampling location using small diaphragm vacuum pumps (Model PAS-3000, Spectrex, Inc.). The samples were typically collected over a two-hour interval. Sample air flow rate measurements were made at the beginning and end of the interval and averaged. Sample volumes, which were corrected to standard conditions of 25° C and one atmosphere pressure, were typically 1.5 - 3 L. Blank field samples were also obtained.

The multisorbent samplers were thermally desorbed, and the samples were introduced into a Hewlett-Packard 5970B gas chromatograph/mass spectrometer (GC/MS) system using a

UNACON 810 concentrating system (Envirochem, Inc.). Prior to analysis, a known amount of bromofluorobenzene was added to each sampler as an internal standard (ISTD). The GC-MS was operated in the SCAN mode over a mass range of  $m/z$  33-300. For the qualitative analysis of individual VOCs contained in the samples, the spectra of peaks in the total-ion-current chromatograms were first compared to spectra contained in a database of commonly occurring VOCs. This database was created in the laboratory from the analyses of pure standards. 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 considered to be confirmed. If no match was obtained, then the spectrum was compared to spectra contained in the NIST electronic database. The analyst decided if an identification was probable based on the match quality and the reasonableness of the retention time. Less certain matches were considered to be tentative. In some cases, no strong match was obtained and the compound was unidentified.

A number of individual VOCs were selected for quantitative analysis based on the qualitative evaluation of the samples. In general, the selected compounds had relatively high abundances and were present in the samples from all sampling periods. Multi-point internal-standard calibrations were prepared for each of the compounds using pure standards. For the more-volatile compounds, gas standards were prepared in static dilution bottles and small volumes of gas were transferred from the bottles to multisorbent samplers using gas-tight syringes. For the less-volatile compounds, the standards were serially diluted in methanol and small aliquots of the diluted standards were added directly to all-Tenax samplers. Standards were analyzed with the same procedures used for field samples.

For the quantitative analysis of TVOC in a sample, the TIC chromatogram was integrated over its entire retention time interval using parameters that captured almost all of the TIC area in the sample. The integrated areas less the area of the ISTD were summed. The mass of the compounds represented by the sum was calculated based on the known amount of ISTD that was added to the sampler. This calculation used an average per-unit mass response factor determined for 13 common alkane and aromatic hydrocarbons relative to the per-unit mass response of the ISTD. Because there is variation in the TIC response of different classes of compounds, the measurement of TVOC is generally less accurate than the calibrated measurement of individual VOCs. Wallace, *et al.* (1991) estimated that the uncertainty in this method is about 30 - 40 percent.

### **Sampling and Analysis of Formaldehyde**

Samples for the analysis of formaldehyde were collected on DNPH-Silica Sep Pak cartridges (Part number 37500, Waters Corp.). An air sample was pulled through a cartridge with a diaphragm vacuum pump. The 2,4-dinitrophenylhydrazine (DNPH) reagent in the cartridge

reacts with carbonyl compounds in the air to form the stable hydrazone derivatives which are retained by the cartridge. A single sample was collected at each indoor sampling location over a two-hour interval. Outdoor and field blank samples were also collected. Sample air flow rate measurements were made at the beginning and end of the interval and averaged. The sample volumes were typically about 35 standard liters (25° C, 1 atm. pressure).

For the analysis of formaldehyde, a sample cartridge was extracted with 2 mL of HPLC-grade acetonitrile. An aliquot of the extract was analyzed for the formaldehyde hydrazone derivative using reverse-phase high-performance liquid chromatography (HPLC) with UV detection. The absorbance of the formaldehyde derivative was measured at 360 nm. The mass response of the resulting peak was determined using a multi-point calibration curve prepared from standard solutions of the formaldehyde hydrazone derivative.

### **Ventilation Rate Measurements**

Infiltration was measured on each level of House A, including the finished basement, concurrently with the collection of samples for airborne contaminants during the November, 1993, and February, 1994, sampling periods. In July, 1994, approximately one-week of continuous infiltration measurements were made in both houses about two weeks after the samples for airborne contaminants had been collected. Sulfur hexafluoride (SF<sub>6</sub>) was used as the tracer gas for these measurements. The concentrations of the tracer gas were determined with a photo acoustic infra-red analyzer (Model 1302 Multi-gas Monitor, Bruel & Kjaer). The tracer gas was injected into the return air stream of the heating/cooling system while the system was in operation to provide mixing of the gas throughout the house. The measurement of the decay in tracer gas concentration began after a 40 - 60 minute mixing period and continued for two hours with a sampling interval of approximately 2.5 minutes. This process was repeated on all three levels of the house. Ventilation rates were determined from the decays in the concentrations of SF<sub>6</sub> using a least squares regression analysis.

In July, 1994, the outdoor weather conditions were similar during the periods of sample collection and infiltration measurement. Therefore, the ventilation rates for this sampling period were estimated for each house with a multiple linear regression algorithm developed from the week of tracer gas measurements. Indoor-outdoor temperature differentials, wind speeds and the fractions of time that the air conditioner was operating were used as inputs to the model.

No ventilation rate measurements were made in House B in July and August, 1995. During this period, the outdoor temperature was substantially elevated over the outdoor temperature in July of the previous year when the infiltration measurements were made in this house. In addition, the energy-recovery ventilation (ERV) system that had been operating continuously in House B failed between July when the formaldehyde samples were collected and

August when the VOC samples were collected. Therefore, the 1995, ventilation rates for House B were estimated using an infiltration model (Sherman and Modera, 1984). This model uses a number of inputs including indoor and outdoor temperatures, wind speed and direction, building parameters and terrain factors. For July, the ERV system ventilation rate of about  $0.33 \text{ h}^{-1}$  was added to the modeled value to obtain an estimated ventilation rate.

### Emission Measurements

Oriented strand board (OSB), which is composed of bonded wood chips, was a major construction material for both houses. In the interiors, OSB was used as the subflooring for the first and second floors. A sample of OSB was collected from the subfloor of House B in September, 1995. Upon collection, the sample was wrapped in aluminum foil and shipped to the laboratory. In the laboratory, the sample was evaluated for its emissions of TVOC, individual VOCs and formaldehyde following the general procedures outlined in ASTM D5116-90 (ASTM, 1990). In brief, the sample was placed in a 10.5-L stainless-steel environmental chamber ventilated with humidified nitrogen at an inlet flow rate of  $0.06 \text{ m}^3 \text{ h}^{-1}$  and maintained at  $23 \pm 1^\circ \text{ C}$  and  $50 \pm 5$  percent relative humidity. Samples were collected from the gas exiting the chamber at 24-h elapsed time and analyzed for TVOC, VOCs and formaldehyde using the procedures described above.

### Data Analysis

Quasi steady-state source strengths ( $\text{mg h}^{-1}$ ) of TVOC, individual VOCs and formaldehyde in the houses were calculated using the following equation:

$$S = V a (C - C_o) \quad (1)$$

where  $V$  is the volume of the study space ( $\text{m}^3$ );  $a$  is the ventilation rate for the space ( $\text{h}^{-1}$ );  $C$  is the concentration of the analyte in the space ( $\text{mg m}^{-3}$ ); and  $C_o$  is the outdoor concentration of the analyte ( $\text{mg m}^{-3}$ ). The model assumes that conditions had reached steady state with constant emissions and a constant ventilation rate. The model further assumes that the air in the space was perfectly mixed and that there were no losses of the analyte through chemical reactions or sorption onto interior surfaces. Since there were small differences among the ventilation rates for the different floors of the houses in the 1993 and 1994 sampling periods, the source strengths for these sampling periods were first calculated for each floor of a house using the volume, ventilation rate and concentrations for that floor and then averaged to obtain an average value for the house. For the 1995 sampling period when the ventilation rates for House B were estimated with an



infiltration model, source strengths for the entire house were calculated using house average values for the relevant parameters.

Equation 1 was also used to calculate the source strengths of TVOC, VOCs and formaldehyde emitted by the material sample. Background concentrations of the analytes ( $C_0$ ) were measured in a blank chamber run. Source emission rates ( $\text{mg m}^{-2} \text{h}^{-1}$ ) of the analytes were determined by dividing the source strengths by the surface area of the material sample ( $\text{m}^2$ ).

## RESULTS AND DISCUSSION

### TVOC

The concentrations and source strengths of TVOC measured in House A in November, 1993, February, 1994, and July, 1994, and in House B in July, 1994, and August, 1995, are summarized in Table 1. In House A in November, TVOC was quantified for the second-floor master bedroom and the first-floor family room only, and in February, TVOC was quantified for the master bedroom and the basement only. In July, 1994, and August, 1995, TVOC was quantified for all three floors of both houses. The concentrations shown in Table 1 are the averages of all of the available data from each sampling period.

The average TVOC concentration in House A ranged from a low of  $1,680 \mu\text{g m}^{-3}$  in February, 1994, to a high of  $4,350 \mu\text{g m}^{-3}$  in July. The high value coincided with the lowest ventilation rate which was calculated to be  $0.075 \text{ h}^{-1}$ . The average TVOC concentrations measured in House B were  $2,840$  and  $2,430 \mu\text{g m}^{-3}$ . These values can be compared to TVOC measurements for samples collected by the U.S. EPA's Total Exposure Assessment Methodology (TEAM) Studies (Wallace, *et al.*, 1991). The TEAM samples were analyzed using a similar method. For a sample of 198 residences representing a population of about 600,000 in six geographical areas of the U.S., the median indoor TVOC concentration was  $700 \mu\text{g m}^{-3}$ . Thus, the TVOC concentrations in Houses A and B were elevated compared to typical residential values. However, TVOC concentrations in new structures are often higher. The TEAM studies also measured TVOC concentrations in ten larger buildings, three of which were new. The median indoor concentration in these ten buildings was  $1,900 \mu\text{g m}^{-3}$ , with the new buildings generally having the highest concentrations. This suggests that the TVOC concentrations measured in Houses A and B may be in a range that is typical for new structures.

Differences in TVOC measurements between the two houses and temporal variations in TVOC measurements are best compared using the calculated steady-state source strengths. With this parameter, differences in the emissions of VOCs can be viewed independently of ventilation rate. It should be noted that there may be considerable uncertainty in the 1995 ventilation rates for House B as these values were estimated with an infiltration model. Table 1 shows that House B had the highest source strength of TVOC of  $729 \text{ mg h}^{-1}$  just after the interior

was completed. This was twice the initial value for House A. In House A, the source strength declined from 385 to 219 mg h<sup>-1</sup> over a three-month period following completion of the interior; after another five months, there was essentially no change as the calculated source strength was 230 mg h<sup>-1</sup>. In House B, the source strength decreased by a factor of four to 180 mg h<sup>-1</sup> over the course of a year. There is no available database of TVOC source strengths in residences for comparison with these values as ventilation rates are typically not measured in conjunction with the collection of indoor air quality samples.

### Formaldehyde

Table 2 shows the concentrations and source strengths of formaldehyde for the two houses. In House A, the formaldehyde concentration ranged from a low of 15 µg m<sup>-3</sup> (13 ppb) in February, 1994, to a high of 74 µg m<sup>-3</sup> (60 ppb) in July, 1994. The concentration in House B was 49 µg m<sup>-3</sup> (40 ppb) in July, 1994, and 59 µg m<sup>-3</sup> (48 ppb) in July, 1995. These values are all less than the ASHRAE and World Health Organization guidelines of 100 ppb. In a study of 51 non manufactured houses in California, the geometric mean concentration of formaldehyde was 35 ppb (Sexton, *et al.*, 1986). Thus, the formaldehyde concentrations in Houses A and B were generally consistent with typical residential indoor values, with the possible exception of the highest value measured during the period of very low ventilation in House A.

House B had the highest source strengths for formaldehyde of 13 - 19 mg h<sup>-1</sup>. The source(s) of formaldehyde in this house did not decrease with time. The initial source strength of formaldehyde in House A was a factor of two to three lower than the source strengths in House B. The source strength in House A declined over a period of three months following completion of the interior to 1.8 mg h<sup>-1</sup>. Five months later in July, 1994, the value was 3.6 mg h<sup>-1</sup>. The increase between February and July in House A may have been related, at least in part, to the somewhat higher indoor temperatures in July (Table 2), as the emissions of formaldehyde from composite wood materials in houses have been shown to have a strong temperature dependence (Matthews, *et al.*, 1986).

### Individual VOCs

Twelve individual VOCs were quantified in the 1993, and February, 1994, samples. These compounds are: toluene, combined m,p-xylene isomers and styrene (aromatic hydrocarbons or HCs); alpha-pinene, d-limonene, n-undecane, n-dodecane and n-tridecane (other HCs); and 2-propanone (acetone), pentanal, hexanal and combined 2,2,4-trimethyl-1,3-pentandiol monoisobutyrate (Texanol) isomers (oxidized compounds). Five additional compounds were quantified in July, 1994, and August, 1995. These are: 1,2,4-trimethylbenzene (aromatic HC); and the aldehydes, heptanal, octanal, nonanal and decanal (oxidized compounds).

The selected compounds were generally the most abundant compounds in the samples. Texanol is used as a coalescing aid in latex paints. The sources of the other compounds are more difficult to ascertain. Toluene, xylenes and acetone are common solvents with a variety of potential sources. One possible source of styrene is expanded polystyrene foam insulation. Wood emits terpene hydrocarbons such as alpha-pinene and d-limonene; however, there are other common sources of these compounds as they are frequently used as odorants in cleaning products. Aldehydes are common constituents of indoor air, but the sources of these compounds are poorly understood.

In general, the dominant compounds in both houses were toluene, alpha-pinene, d-limonene, acetone, pentanal and hexanal. The overall similarity in the composition of VOCs between the two houses suggests that the sources of these compounds may have been common to both houses. In House A, the highest concentrations of the individual compounds generally occurred in the July, 1994, sampling period when the ventilation rate was very low. The exceptions were m-,p-xylene, styrene, n-undecane and Texanol. In House B, the highest concentrations of individual compounds generally occurred in August, 1995, also when the ventilation rate was low. The exceptions were m-,p-xylene, 1,2,4-trimethylbenzene, n-dodecane, n-tridecane and Texanol.

Among the target compounds, the C<sub>5</sub> - C<sub>10</sub> aldehydes (pentanal - decanal) have the lowest odor thresholds (Devos, *et al.*, 1990). The highest concentrations of these compounds in Houses A and B are compared to their respective odor thresholds in Table 4. In general, the concentrations of pentanal - decanal measured in both houses in July, 1994, and in House B in August, 1995, either closely approached or were in excess of their respective odor thresholds. The odor threshold for hexanal of 58 µg m<sup>-3</sup> was significantly exceeded by all of the measured indoor concentrations of this compound.

The calculated steady-state source strengths of the individual VOCs are shown in Table 5. Five of the twelve compounds had significantly higher initial source strengths in House B (July, 1994) than in House A (November, 1993). These compounds are m-,p-xylene, alpha-pinene, n-dodecane, pentanal and hexanal.

In House A, the source strengths of alpha-pinene, pentanal and hexanal were noticeably higher in July, 1994, than in November, 1993. This general pattern of increasing source strengths with time is unexpected in an unoccupied house. The source strengths of styrene, d-limonene, n-dodecane and n-tridecane remained relatively constant over the same period while the source strengths of toluene, m-,p-xylene, n-undecane, acetone and Texanol declined significantly. In House B, the source strengths of all compounds decreased from July, 1994, to August, 1995. However, for toluene, styrene, alpha-pinene, acetone and pentanal the decline was less than 50 percent. The distinct decline in the source strengths of Texanol with time in both houses was

undoubtedly due to the decrease in the emissions of Texanol from the interior paint as the paint aged.

Interestingly, the ratios of the source strengths of alpha-pinene, pentanal and hexanal are similar for all of the samples from both houses. This suggests that these compounds may have been emitted by a single source. The average combined source strength of alpha-pinene, pentanal and hexanal in House B for the two sampling periods is  $139 \text{ mg h}^{-1}$ . Assuming that these compounds derived from one source with continuous and relatively constant emissions, the total emissions of these three compounds over the course of the year is estimated to be in excess of one kilogram (*i.e.*,  $1.4 \cdot 10^{-4} \text{ kg h}^{-1} \times 8.8 \cdot 10^3 \text{ h yr}^{-1}$ ). If so, the source itself must have had substantial mass and is likely to have been a major building component.

The emission rates of TVOC, formaldehyde and six individual VOCs from the sample of OSB obtained from House B are presented in Table 6. The six VOCs are the only compounds emitted by the OSB that were also quantified in the houses. Neither alpha-pinene nor d-limonene were detected in the emissions from the OSB, strongly suggesting that OSB was, at least, not a long-term source of these compounds. Together, the six VOCs comprised about 30 percent of the TVOC emissions from the OSB sample. Acetic acid (data not shown) was roughly estimated to comprise approximately another 40 percent of the TVOC emissions from the OSB. Among the individual compounds, formaldehyde, acetone and hexanal had the highest OSB emission rates.

Since the floors of the houses were completely covered, largely with carpet, the emission rates of VOCs from the OSB flooring in the houses may have been substantially different than those measured in the small chamber. Nevertheless, source strengths potentially due to emissions from the OSB flooring were estimated for House B by multiplying the OSB emission rates by the approximate floor area of OSB (Table 6). These source strengths can be compared to the corresponding source strengths estimated for House B in August, 1995, from the house concentration and ventilation rate data (Tables 1, 2 and 5). Interestingly, the source strengths of formaldehyde and acetone for the OSB are substantial fractions of the house source strengths of these compounds at 0.4 and 0.3, respectively. The OSB source strengths for the remaining compounds are only small fractions of the corresponding house source strengths. This suggests that OSB was probably not the dominant source of these compounds in these houses.

## CONCLUSIONS

Several conclusions can be drawn from this study. First, the ventilation rates in House A were too low. In November and February, the ventilation rates were  $0.2 - 0.3 \text{ h}^{-1}$ , and in July the rate was less than  $0.1 \text{ h}^{-1}$ . The ventilation rates would presumably be higher if the house was occupied, but there might be periods in which the house would be entirely closed, particularly if all of the occupants were away from home during the day. Concentrations of VOCs emitted by

indoor material sources would build up during these periods of low ventilation, resulting in elevated occupant exposures to these compounds. Thus, in houses with tight envelopes, such as these, it is advisable to maintain some level of constant mechanical ventilation. An ERV system was installed in House B to achieve a constant ventilation rate of about  $0.4 \text{ h}^{-1}$ . Unfortunately, this system failed prior to the collection of samples in August, 1995. If the ERV system had been operating at that time, the indoor concentrations of VOCs would, most likely, have been substantially lower since the source strengths of most VOCs in this house had declined during the year.

The concentrations of pentanal, hexanal, octanal and nonanal were generally found to be elevated compared to their respective odor thresholds. Therefore, it is likely that these compounds had an adverse odor impact in these houses.

The study illustrated the utility of the mass-balance approach in indoor air quality investigations. The use of source strengths allowed comparisons to be made among VOC measurements in two houses and for different sampling periods in the same house in which the ventilation conditions were not equivalent. In addition, it was possible to compare source strengths of compounds measured in a small-scale chamber for a material source to the corresponding source strengths estimated from the house data. This mass-balance approach would have been more robust if the ventilation rate determinations had been performed in a consistent manner throughout the study.

The persistently elevated and, in some cases, increasing source strengths of several VOCs in these houses are puzzling and raise questions about the possible emission source(s) of these compounds. It is generally expected that the source strengths of compounds emitted by most materials used to finish the interiors of houses will decrease with time as the materials age and that substantial decreases in source strengths will be obtained over a period of a few months. This behavior was shown, for example, by the large decreases with time in the emissions of Texanol from the interior paint. Nearly constant or increasing source strengths could result from several possible causes. An active source, such as a cleaning product, might have been used in the houses, although this is unlikely. The source might have been a material for which the emissions had a strong temperature dependence. In House A, the highest indoor temperatures occurred in July coincidentally with some of the highest source strengths while in House B the indoor temperatures were nearly equivalent for both sampling periods. Another possibility, is that the source was covered by a diffusion barrier with a relatively long retardation time. This scenario might result in prolonged elevated source strengths or even in source strengths with an apparent increase with time.

The measurement of emissions of VOCs from OSB in a small-scale chamber suggested that this material might have been a significant source of formaldehyde and acetone in the

houses. It also suggested that OSB was not the dominant source of alpha-pinene, pentanal and hexanal, which all had elevated emissions, possibly from a single source. Therefore, more investigation is needed to identify the dominant source(s) of VOCs in these houses.

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Table 1. Ventilation rates and average concentrations and steady-state source strengths of TVOC in House A in November, 1993, February, 1994, and July, 1994, and in House B in July, 1994, and August, 1995.

House	Date mon./yr.	Vent. Rate (h <sup>-1</sup> )	Conc. (µg m <sup>-3</sup> )	Source Str. (mg h <sup>-1</sup> )
A <sup>a</sup>	11/93	0.22	2,390	385
A <sup>b</sup>	02/94	0.20	1,680	219
A	07/94	0.075 <sup>c</sup>	4,350	230
B	07/94	0.38 <sup>c</sup>	2,840	729
B	08/95	0.11 <sup>d</sup>	2,430	180

a. 1st and 2nd Floors only.

b. 2nd Floor and Basement only.

c. Ventilation rate was estimated from data obtained two weeks after collection of samples.

d. ERV system failed; ventilation rate was estimated using an infiltration model.

Table 2. Average concentrations and steady-state source strengths of formaldehyde in House A in November, 1993, February, 1994, and July, 1994, and in House B in July, 1994, and July, 1995.

House	Date mon./yr.	Avg. Temp. (°C)	Vent. Rate (h <sup>-1</sup> )	Conc. (µg m <sup>-3</sup> )	Source Str. (mg h <sup>-1</sup> )
A	11/93	19.4	0.30	34.8	6.44
A <sup>a</sup>	02/94	20.7	0.20	15.4	1.84
A	07/94	22.9	0.069 <sup>b</sup>	73.8	3.59
B	07/94	22.6	0.39 <sup>b</sup>	48.9	13.1
B	07/95	23.5	0.45 <sup>c</sup>	59.4	19

a. 2nd Floor and Basement only.

b. Ventilation rate was estimated from data obtained two weeks after collection of samples.

c. ERV system operational; ventilation rate was estimated using an infiltration model.



Table 3. Average concentrations of individually quantified VOCs in House A in November, 1993, February, 1994, and July, 1994, and in House B in July, 1994, and August, 1995.

Compound	Concentration ( $\mu\text{g m}^{-3}$ )				
	House A <sup>a</sup> 11/93	House A <sup>b</sup> 02/94	House A 07/94	House B 07/94	House B 08/95
<b>Aromatic HCs</b>					
Toluene	114	37.6	121	62.7	113
m-,p-Xylene	10.8	8.1	6.3	53.3	27.8
Styrene	3.3	15.8	10.4	3.8	9.8
1,2,4-Trimethylbenzene	NA	NA	24.4	163	77.4
<b>Other HCs</b>					
alpha-Pinene	76.1	154	363	224	502
d-Limonene	48.4	41.8	131	54.8	80.2
n-Undecane	52.7	24.1	46.8	21.2	21.2
n-Dodecane	10.1	8.0	49.3	28.2	7.5
n-Tridecane	7.1	10.2	35.3	6.7	4.3
<b>Oxidized Cmpds.</b>					
Acetone	167	49.3	267	131	266
Pentanal	37.0	28.3	243	83.4	203
Hexanal	142	195	956	393	502
Heptanal	NA <sup>c</sup>	NA	51.6	21.9	30.5
Octanal	NA	NA	NA	44.2	46.8
Nonanal	NA	NA	79.4	44.3	57.3
Decanal	NA	NA	<2.0	4.8	13.0
Texanol	42.1	11.3	14.8	13.0	<2.0

a. 1st and 2nd Floors only.

b. 2nd Floor and Basement only.

c. NA = Not analyzed.

Table 4. The maximum concentrations of the aldehydes, pentanal through decanal, in Houses A and B compared to standardized odor thresholds as summarized by Devos, *et al.*, 1990.

Compound	Odor Threshold	Concentration ( $\mu\text{g m}^{-3}$ )	
		House A Maximum	House B Maximum
Pentanal	22	243	203
Hexanal	58	956	502
Heptanal	23	51.6	30.5
Octanal	7	NA <sup>a</sup>	46.8
Nonanal	13	79.4	57.3
Decanal	6	<2.0	13.0

a. NA = Not analyzed.

Table 5. Average steady-state source strengths for individually quantified VOCs in House A in November, 1993, February, 1994, and July, 1994, and in House B in July, 1994, and August, 1995.

Compound	Source Strength (mg h <sup>-1</sup> )				
	House A <sup>a</sup> 11/93	House A <sup>b</sup> 02/94	House A 07/94	House B 07/94	House B 08/95
<b>Aromatic HCs</b>					
Toluene	18.5	4.63	6.46	16.0	8.6
m-,p-Xylene	1.57	0.88	0.13	13.8	2.1
Styrene	0.55	2.12	0.56	0.93	0.7
1,2,4-Trimethyl- benzene	NA	NA	0.77	42.7	6.1
<b>Other HCs</b>					
alpha-Pinene	12.4	20.6	19.0	56.6	39
d-Limonene	8.00	5.63	7.09	14.2	6.4
n-Undecane	8.52	3.20	2.44	5.06	1.6
n-Dodecane	1.66	1.07	2.62	7.19	0.5
n-Tridecane	1.17	1.38	1.97	1.81	0.3
<b>Oxidized Cmpds.</b>					
Acetone	26.6	6.5	14.3	33.4	22
Pentanal	6.19	3.81	13.6	23.4	16
Hexanal	23.5	26.0	52.1	103	40
Heptanal	NA <sup>c</sup>	NA	2.89	6.12	2.3
Octanal	NA	NA	NA	9.08	3.5
Nonanal	NA	NA	3.93	9.84	3.8
Decanal	NA	NA	<0.3	<0.3	<0.3
Texanol	6.92	1.44	0.76	3.29	<0.3

a. 1st and 2nd Floors only.

b. 2nd Floor and Basement only.

c. NA = Not analyzed.

Table 6. Emission rates of TVOC, formaldehyde and individually quantified VOCs from a sample of oriented strand board (OSB) obtained from House B in September, 1995. Source strengths for House B were estimated by multiplying the emission rates by the approximate floor area of OSB.

Compound	Emission Rate ( $\mu\text{g m}^{-2} \text{ h}^{-1}$ )	Estimated Source Strength ( $\text{mg h}^{-1}$ )
TVOC	234	50.0
Formaldehyde	36.3	7.8
Acetone	30.7	6.6
Pentanal	9.0	1.9
Toluene	1.9	0.4
Hexanal	18.0	3.8
Heptanal	1.2	0.3
Octanal	1.5	0.3



