Identifying Sources of Volatile Organic Compounds and Aldehydes in a High Performance Building

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DISCLAIMER

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ABSTRACT

The developers of the Paharpur Business Center (PBC) and Software Technology Incubator Park in New Delhi, India offer an environmentally sustainable building with a strong emphasis on energy conservation, waste minimization and superior indoor air quality (IAQ). To achieve the IAQ goal, the building utilizes a series of air cleaning technologies for treating the air entering the building. These technologies include an initial water wash followed by ultraviolet light treatment and biolfiltration using a greenhouse located on the roof and numerous plants distributed throughout the building. Even with the extensive treatment of makeup air and room air in the PBC, a recent study found that the concentrations of common volatile organic compounds and aldehydes appear to rise incrementally as the air passes through the building from the supply to the exhaust. This finding highlights the need to consider the minimization of chemical sources in buildings in combination with the use of advanced air cleaning technologies when seeking to achieve superior IAQ. The goal of this project was to identify potential source materials for indoor chemicals in the PBC. Samples of building materials, including wood paneling (polished and unpolished), drywall, and plastic from a hydroponic drum that was part of the air cleaning system, were collected from the building for testing. All materials were collected from the PBC building and shipped to the Lawrence Berkeley National Laboratory (LBNL) for testing. The materials were pre-conditioned for two different time periods before measuring material and chemical specific emission factors for a range of VOCs and Aldehydes. Of the six materials tested, we found that the highest emitter of formaldehyde was new plywood paneling. Although polish and paint contribute to some VOC emissions, the main influence of the polish was in altering the capacity of the surface to accumulate formaldehyde. Neither the new nor aged polish contributed significantly to formaldehyde emissions. The VOC emission stream (excluding formaldehyde) was composed of up to 18 different chemicals and the total VOC emissions ranged in magnitude from 7 $\mu g/m^2/h$ (old wood with old polish) to >500 $\mu g/m^2/h$ (painted drywall). The formaldehyde emissions from drywall and old wood with either new or old polish were ~ 15 $\mu g/m^2/h$ while the new wood material emitted > 100 $\mu g/m^2/h$. However, when the projected surface area of each material in the building was considered, the new wood, old wood and painted drywall material all contributed substantially to the indoor formaldehyde loading while the coatings contributed primarily to the VOCs.

INTRODUCTION

Features of the seven-story Paharpur Business Center (PBC) and Software Technology Incubator Park in New Delhi India have been described [1,2]. A notable feature of the building is the stated goal of providing a healthy work environment for building occupants with specific interest in maintaining superior indoor air quality (IAQ) [1]. To achieve this goal, the building utilizes several innovative air cleaning technologies, such as air washing to remove the more polar volatile contaminants, bio-filtration of building makeup air using an enclosed rooftop greenhouse with a high density of potted plants, passive treatment of indoor air using a large number of potted plants distributed throughout the building, dedicated secondary heating, ventilation and air conditioning (HVAC) air handling units on each floor with re-circulating high efficiency filtration and ultraviolet light treatment of heat exchanger coils, and air exhaust via the restrooms located on each floor. The idea of using potted plants to remove VOCs from the indoor environment was originally introduced by Wolverton et.al. [3, 4]. In addition to treating the air, the PBC management recognizes the importance of reducing potential sources of indoor chemicals by providing environmentally friendly cleaning products exclusively for the building and selecting certain materials during renovations including a combination of stone, tile and 'zero VOC' floor covering and solid sawn wood materials for trim, paneling and furniture, with minimal use of composite wood products [2].

A recent short-term field study collected indoor air quality measurements at the PBC to investigate the performance of the biofiltration air cleaning system [2]. The study focused primarily on VOCs and aldehydes and collected measurements at several locations in the building representing the transfer pathway of air moving through the building starting on the roof outdoors and following through the rooftop greenhouse, indoors on two floors, and at the building exhaust locations. The study found that for most contaminants, the levels of common indoor VOCs and aldehydes generally increased as the air moved through the building, indicating the presence of indoor sources. The study concluded that even with the extensive effort given to maintaining superior IAQ, the building still had concentrations of VOCs and carbonyls similar to that found in other office buildings. However, the authors point out that given the outdoor air quality in New Delhi compared to the outdoor air quality where the comparative IAQ studies have been carried out for other office buildings, the findings of the short-term study may indicate some added benefit of the biofiltration-based air cleaning technology.

The increase in concentration for several VOCs and carbonyls as the air moved through the building indicated the presence of an indoor source for these chemicals. The contribution of indoor chemicals from different building materials and building contents have been investigated for a range of building types [5-8] and typical concentrations measured in these buildings have been summarized [9-14]. The purpose of this project was to investigate the potential source(s) of VOCs and carbonyls in the PBC. Following the short-term testing [2], the building managers identified several potential sources of indoor contaminants including composite wood paneling, painted gypsum board walls and high density plastic barrels used as hydroponic containers for the biofiltration-based air cleaning technology. Both new and aged (~20 year old) plywood wall paneling was present in the building and the paneling was coated with a clear polish. The goal of this study was to measure material specific emission factors for VOCs and carbonyls and characterize the potential influence of the polish coating on the wood panel material.

METHODS

Material Collection and Preparation

All building materials that were tested for emissions were harvested from the PBC building, double wrapped in foil and shipped directly to Lawrence Berkeley National Laboratory for testing. A description of each of the material samples is provided in Table 1. All samples except for the hydroponic drum were cut to 0.023 m^2 (six inches square). In the laboratory, the sides and backs of the material were sealed with aluminum tape and stainless steel backing plates, respectively, to leave only the front face of the material exposed for testing. Each sample was placed individually in 6-liter stainless steel conditioning chamber as illustrated in Figure 1. The conditioning chambers were closed with Teflon lined lids and held at approximately 22 ˚C and 50% relative humidity (RH) to precondition the materials prior to sampling. For new materials, samples are typically preconditioned to allow the emissions to drop to a more relevant value for estimating long-term emission rates. For materials that are allowed to age in the environment, the conditioning period is important to allow chemicals that have partitioned into the material from the environment, e.g., chemicals that are not indigenous to the material, to off-gas so that the measured emission rates are relevant to the material being tested. The conditioning chambers were ventilated with carbon/HEPA filtered air at a rate of 250 cc/min (2.5 air changes per hour or 0.65 $m^3_{[air]}/m^2_{[exposed\ surface\ area]}$/hour).

Material Testing

The emission testing generally followed California Specification 01350 [15] and ASTM Standard Guide D-6007-02 [16] using small emission chambers. The approach has been used for a wide range of materials measuring both VOCs and carbonyls as described previously [8, 17] and as summarized below.

Four emission chambers installed in a controlled environment oven provide an isolated environment with constant temperature and humidity. The constant humidity was maintained by splitting the flow of dry (<5% RH) carbon/HEPA filter air with a portion of the air bubbling through a water bath then re-mixed to achieve the desired humidity for air flowing through each chamber. The chambers, shown in Figure 2, are made of stainless steel and all interior surfaces are coated with Sulfinert® coating to minimize chemical interaction with chamber walls. The chambers are 10.75 L and are operated with an approximate ventilation rate of 1 liter per minute equivalent to 5.6 air changes per hour (ACH), or 2.6 $m^3_{[air]}/m^2_{[exposed\ surface\ area]}$/hour). The standard tests are operated at 25 °C and 50% RH. After being pre-conditioned, each test material was transferred to the test chamber and placed on Sulfinert® treated screens resting slightly below the midpoint of the chamber.

Each material was allowed to equilibrate in the test chamber for at least 30 minutes after being transferred from the conditioning chamber before testing. Once equilibrated, the air samples were collected directly from the test chamber and analyzed for VOC and Aldehydes (ALD) as described below. The materials were first tested after 24 hours of conditioning, and then again after at least seven days of conditioning. The first sampling period was used to get information on upper bound emission rates and allow for the identification of the mix of chemicals in the emission stream. The second sampling period, after seven days conditioning, provides the emission factors that are more relevant to the long-term emission pattern. Additional measurements were collected for the new wood with new polish to further understand how the polish affects the emissions from the material.

Active Sampling for VOC

VOC samples were collected and analyzed following the U.S. Environmental Protection Agency (USEPA) Method TO-17 [18]. VOC air samples were collected directly from the chambers by drawing chamber air through multi-sorbent tubes with a primary bed of Tenax-TA® sorbent backed with a section of Carbosieve®. A peristaltic pump was used to pull the air through the sample tubes at a rate of approximately 100 mL/min for 1 hour. The flow was measured using a DryCal gas flow meter (BIOS, 500 ml/min) and was recorded at the beginning and the end of the sampling period. Before subjected to chemical analysis, each sample was spiked with 120ng of gas-phase 1-Bromo-3 Fluoro-Benzene (BFB), which was used as the internal standard (ISTD) in the quantification method.

Analytes were thermally desorbed from the sampling tubes using a thermodesorption auto-sampler (Model TDSA2; Gerstel), a thermo-desorption oven (Model TDS3, Gerstel), and a cooled injection system (Model CIS4; Gerstel). Desorption was performed in splitless mode where the desorbed analytes were refocused on the cooled injection system prior to injection. Desorption temperature for the TDS started at 30 ˚C with a 0.5 minute delay followed by a 60 ˚C ramp to 250 ˚C and a 4 minute hold time. The cooled injection system was fitted with a Tenax-packed glass liner (P/N 013247-005-00; Gerstel) that was held at -10 ˚C throughout desorption and then heated within 0.2 minutes to 270 ˚C followed by a 3-minute hold time. Compounds were resolved on a GC (Series 6890Plus; Agilent Technologies) equipped with a 30 meter HP-1701 14% Cyanopropyl Phenyl Methyl capillary column (Model 1909IU-233;- Agilent Technologies) with helium flow of 1.2 mL/min. The initial temperature of the oven was -10 ˚C held for 0.5 minutes then ramped at 5 ˚C/min to 40 ˚C then 3 ˚C/min to 140 ˚C and finally at 10 ˚C/min to 250 ˚C and held for 10 minutes.

The resolved analytes were quantified using electron impact mass spectrometry, (MS System 5973; Agilent technologies), with mass to charge ratio limits of 44.0 m/z and 450.0 m/z. The MS was operated in full scan mode with a solvent delay of 3.00 minutes. Compounds were initially identified using NIST mass spectral search program for the NIST/EPA/NIH mass spectral library (version 2.0d build April 26, 2005) with identity confirmed and quantified using pure standards. When pure standards were not available, the analyte was reported in terms of toluene equivalence by comparing the instrument response for the total ion chromatogram (TIC) of the chemical to a multipoint calibration of TIC response for toluene.

Active Sampling for Carbonyl

The volatile carbonyls including formaldehyde, acetaldehyde and acetone are quantified using USEPA Method TO-15 [19]. As with the VOC samples, the air was drawn directly from the chambers during sampling. The sampling rate was maintained at less than 80% of the total air flow through the chamber to prevent backflow of unfiltered air into the chamber during testing. The sample air passed through silica gel cartridges coated with 2,4-dinitrophenyl-hydrazine, which quantitatively reacts with the carbonyl functional group effectively trapping the aldehydes and other low molecular weight carbonyl compounds. A peristaltic pump was used to pull the air through the cartridge at a rate of approximately at 800 mL/min for 1 hour. The flow was measured using a DryCal gas flow meter (BIOS, 5 L/min) and recorded at the beginning and the end of the sampling period. Prior to analysis, sample cartridges were eluted with 2ml of high purity acetonitrile and the effluent was brought to a final volume of 2 ml. The extract was analyzed by high-performance liquid chromatography (HPLC) (1200 Series; Agilent Technologies). The HPLC was fitted with a C18 reverse phase column and run with 65:35 H2O: Acetonitrile mobile phase at 0.35 mL/minute and UV detection at 360 nm. Multipoint calibrations were prepared for the target analytes using commercially available hydrazone derivatives of formaldehyde, acetaldehyde and acetone.

Data Analysis

The emission factors for each sample material were calculated using the information collected from each chamber at steady state conditions. The steady-state form of the mass balance equation for calculating area-specific emission factors, EF_i, (µ/m^2/h) for chemical *i* in a well-mixed system is

$$EF_i = \frac{F \times (C_i - C_{Bi})}{A_m} \tag{1}$$

where F (m^3/h) is the ventilation flow rate, A_m (m^2) is the exposed surface area of test material m, C_i ($\mu g/ m^3$) is the measured steady state concentration of chemical i in the chamber and, C_{Bi}. ($\mu g/ m^3$) is the background concentration in the chamber when empty. The air change rate in the chamber, ACH (1/h) is the ventilation rate divided by the chamber volume (F/V) and the loading factor of the material, L (m^2/m^3), is the exposed surface area of test material divided by the chamber volume, where the equation mentioned above can be rearranged to the form

$$EF_i = \frac{ACH \times (C_i - C_{Bi})}{L_m} \tag{2}$$

which is the equation used to calculate material specific emission factors for all materials in this study. The steady-state mass balance relationship can also be used to convert the material specific emission factors to approximate room concentrations using Equation 3

$$C_i = \frac{EF_i \times L_m}{ACH \times 0.9} \tag{3}$$

Where L_m is now the loading factor for the specific material type in the building or room, and the factor 0.9 is an approximate correction of the total room volume to the volume of accessible space. Further details of this approach can be found in reference [15].

RESULTS AND DISCUSSION

All materials were initially tested after only 24-hours of conditioning time. Prior to conditioning, the materials had been tightly wrapped in foil and packaged individually in resealable plastic bags during shipping so the initial emissions were expected to be elevated. The purpose of this in initial testing was to identify the chemicals in the emission stream. A total of forty chemicals were identified in the emission stream from the six materials tested. All chemicals are listed in Table 2 along with steady state concentrations measured after 24-hours of conditioning. All values are listed in Table 2 for comparision but values above the typical method limit of quantification (LOQ) of 0.5 $\mu g/m^3$ are listed in bold text.

The plastic material from the hydroponic drum was tested as received without sealing the back and sides so the exposed area was approximately double that of the other materials. The initial measurements found that except for hexadecane and tetradecane, most of the VOCs from the plastic material, including the aldehdyes, were near or below the minimum detection limit. Therfore, the plastic is not likely a source of indoor contaminants in the indoor environment of the PBC. The drywall material produced a number of elevated VOCs with two (benzyl alcohol and propylene glycol) that exceeded the linear range of the analytical method. Drywall is typically a low VOC material [17, 20] although fresh coatings such as paint or plaster can emitt VOCs during curing. The drywall samples tested in this study appear to be freshly painted because the edges were sealed with paint. This might explain the elevated propylene glycol and benzyl alcohol. The new wood paneling had very high levels of formaldehyde both with and without polish although the polished panel had the hightest levels of formaldehyde overall. However, the unpolished new wood panel produced a wider variety and higher levels of VOC in the emissions. The old wood paneling produced much lower levels of formaldehyde and the levels of VOCs in general were similar both with new and old polish.

After the initial tests were completed to identify the target chemicals in the emission stream, the materials were returned to the conditioning chambers for approximately six more days before measuring the emission factors. Concentrations for the plastic material from the hydroponic drum remained low in the second test so emission factors are not reported for the plastic hydroponic drum material. The standard emission factors determined for the wood paneling and drywall materials are reported in Table 3. The formaldehyde emissions from new wood with new polish were still significantly elevated after 7 days but we suspected that the combination of polish and storage may have increased the time needed for the emission factor to drop to a relativily constant level. To address this, we continued to condition the new wood with new polish for an additional week (total 15 days total) and re-tested. The additional time needed to condition the new wood with new polish may have been due to a higher capacity of the polish coating for accumulating formaldehyde during storage. This possibility was tested and is discussed further below.

The standard emission factors for the materials from the PBC are summarized in Table 3. Several of the chemicals that were initially detected in the materials were no longer detectable in the emission stream after a week of conditioning and are therfore not listed in Table 3. The painted drywall continued to have extremely high levels of benzyl alcohol and propylene glycol as well as quantifiable levels of several other aldehydes (formaldehyde, benzaldehyde, decanal and nonanal), alcohols and esters that may be related to the coating material and/or sorbed into the drywall matrix from the environment. The wood paneling material presented a mix of VOCs depending on if the polish and/or wood were new or old as illustrated in Figure 3. Figure 3 lists the sum of all emission factors for VOC presented as stacked colums with the largest overall emission factors listed in decreasing order from bottom to top on the figure legend. Emission factors listed in Table 3 that are below the approximate limit of quantification of 1.65 $\mu g/m^2/h$ are not included in Figure 3. Overall the drywall material had the highest sum of individual emission factors (516 $\mu g/m^2/h$) with the paneling material emitting 134, 129, 33 and 7 ($\mu g/m^2/h$) for the new wood no applied polish, old wood new polish, new wood new polish and old wood old polish, respectivily.

Formaldehyde emissions for the old wood paneling with new and old polish, and the drywall were all similar ranging from 10 $\mu g/m^2/h$ (drywall and old wood with new polish) to 22 $\mu g/m^2/h$ (old wood with old polish). For the new wood, the formaldehyde emissions were approximately an order of magnitude higher than the other materials for both the polished and unfinished surfaces. The emission results for formaldehyde are illustrated in Figure 4 showing that the polish coating does not seem to significantly change the measured emission factors when the age of the wood paneling is taken into consideration. For old wood, the new polish slightly reduces the emission factor while for new wood the polish increases the emission factor slightly but the difference is likley more a function of the age of the wood than the polish. For example, given the old wood where the emissions are already low, adding the new polish may provide an apparent sink for the formaldehyde as it accumulates in the coating. In contrast, for the new wood, the initial emission rate is high and the coating may simply add a diffusion layer that increases the time that the emission from the wood paneling takes to drop to a constant level. With or without the coating, the new wood is clearly the major source of formaldehyde emissions among the materials tested.

The aging of the formaldehyde emissions and the affect of the polish coating were tested further by removing the backing plate from the new wood with new polish after the initial conditioning and testing period was complete and reversing the material to expose the unfinished face. Our premise was that the formaldehyde diffuses to and accumulates at the surface of the material when the surface is covered so the initial emissions after uncovering the surface are expected to be high then drop with time towards an constant value. The results are illustrated in Figure 5. The initial test of the polished side was repeated 4 times over 15 days. To test the emissions of aldehydes from the unfinished side of the same new wood material, the sample was flipped to expose the unfinished side and the polished side was sealed and the sample was returned to the test chamber (without conditioning) to test the unfinished face. The first measurement found formaldehyde emissions from the unfinished face significantly in excess of the polished side but the emissions decreased rapidily over the next week. The material was flipped again exposing the poished side again that had been sealed for a week and the emission factor doubled (109 $\mu g/m^2/h$ to 217 $\mu g/m^2/h$) but resumed dropping over the next day. Overall, the results indicate that the emission factor of formaldehyde from the new wood with new polish is approaching that of the new wood with no applied polish over time.

The standard emission factors for formaldehyde from each of the main wall surface materials (drywall, old wood and new wood) listed in Table 3 are compared to field measured values for the PBC building that were collected previously using Equation 3 along with the building parameters listed in Table 4. The results are listed in Table 5 for each material and each floor as a range of concentrations estimated with ACH values representing the maximum and 50% of the maximum accounting for the fact that the demand response system will likely run the ventilation at less than the maximum value. These ranges are summed for the total wall area based on loading factors for each material and the range of total concentraions are compared to the measurements in the last row of the table. Assuming no other significant loss pathways for formaldehyde, the three primary wall materials can easily account for the measured concentrations.

CONCLUSION

From the building materials that were supplied to LBNL for testing, it was determined that the formaldehyde levels measured in the PBC can be accounted for by emissions from old wood paneling, painted drywall and new wood paneling. Overall, the highest emitter of formaldehyde was new wood paneling and, although the surface polish affected the time to steady state, polish did not generally increase the amount of formaldehyde released. The aging of the new paneling will likely result in a reduction in formaldehyde emissions to a value that is similar to that of the old paneling. This reduction of emission with time has been observed in a number of buildings [12]. It is possible that the wood polish provides a reservoir for indoor contaminants as indicated by the fact that a number of VOCs and aldehydes detected after the materials were conditioned for only a day dropped below detection levels after a week of conditioning, indicating that these contaminants were not indigenous to the materials being tested but had partitioned into these materials from the environment. Although the polish was not found to contribute to formaldehyde emissions, the polish does contribute to VOC emissions for some chemicals as seen by comparing the polished and unpolished side (data not shown) of one of the materials. Painted surfaces of drywall were also found to be significant contributors to a range of VOCs particularly those related to the coating. It may be that the coating on the drywall material was fresh and the emissions will drop with time as the paint cures. Nonetheless, the painted drywall sample tested during this project clearly had elevated levels of VOCs related to the coating.

This study considered only the materials that were provided to LBNL for testing. There may be other sources present in the building, both continuous and intermittent, which may influence the indoor concentrations of chemicals. Considering only the materials included in this study, the modeling indicates that formaldehyde concentrations on the fifth floor should be lower than that on the third floor but the measurements collected in the previous field study were similar. This may indicate that other unidentified sources or contaminant removal pathways are present in the building.

The tradeoff between having high quality aesthetically pleasing materials in the indoor environment and introducing unanticipated contaminants into the space is a difficult one. Aged materials seem to contribute minimal amounts of VOCs and aldehdyes but better understanding of the temporal characteristics of the aging process would provide important opportunities to optimize the ventilation and air treatment options after renovations or during episodic increases in chemical loading. In addition, further work should consider potential secondary source of contaminants such as the degradation of alkenes and higher molecular weight carbonyls under UV light treatment in the air handling system or potential degradation of polish and other coating materials.

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Table 1. PBC Building Material Samples

Sample Type	Description	Identification
Wood	New plywood paneling with new polish[1]	NWNP
Wood	New plywood paneling with no applied polish (bare wood)	NW
Wood	Old plywood paneling (~ 20 years) with new polish	OWNP
Wood	Old plywood paneling (~ 20 years) with old polish	OWOP
Gypsum board	Drywall with painted finish. All surfaces of the sample including edges were painted	GB
High Density Plastic	Hydroponic drum material used in air cleaning system	HDP

[1] Both the front face (polished) and the back face (unpolished) of this material were tested over the course of the study to further understand the contribution of the polish to the emission stream and the affect that polish might have on emissions from the underlying material.

Table 2. Measured air concentrations (μg m^{-3}) of identified chemicals in test chamber after 24-hour conditioning period.

			Material Description			
	Old Wood		New Wood		DryWall	Plastic
Chemical Name	Old Polish	New Polish	No Polish	New Polish	Painted	Hydro-Drum
Formaldehyde	**9.86**[a]	**5.75**	**50.37**	**315.91**	**4.74**	0.19
Acetaldehyde	**1.22**	0.49	0.16	0.20	**0.53**	**0.53**
Acetone	0.36	1.39	nd[c]	nd	nd	nd
Benzaldehyde	0.11	0.13	**1.03**	0.08	**7.73**	0.14
Benzyl Alcohol[b]	0.40	0.46	**47.54**	0.05	**>80**[d]	nd
1-Butanol	**1.42**	**1.48**	**2.26**	nd	**2.38**	nd
2-Butanol	**0.87**	**0.88**	**2.02**	nd	**0.78**	nd
2-Butoxyethanol	**0.85**	**1.10**	**2.80**	nd	**0.84**	nd
n-Butyl Laurate	nd	**1.01**	0.16	0.43	nd	nd
3-Carene	0.07	0.08	0.12	0.04	**37.83**	0.23
Decamethylcyclopentasiloxane	0.41	0.01	0.07	0.04	0.21	0.01
Decanal	**1.10**	0.30	**0.63**	0.14	0.18	nd
1,4-Dichlorobenzene	0.14	0.10	0.10	0.05	**2.49**	0.22
Diethylphthalate	0.14	0.13	0.26	0.23	0.15	0.03
Dodecanoic acid, 1-methylethyl ester	nd	**0.51**	**0.55**	**0.76**	nd	0.13
Ethanol, 2-(2-butoxyethoxy)-	nd	0.14	**9.21**	nd	**4.30**	nd
Ethylbenzene	0.02	nd	0.05	nd	0.04	nd
Hexadecane	nd	nd	nd	nd	nd	**1.00**
Hexanal	0.20	0.13	0.42	0.48	**0.56**	0.02
Hexanedioic acid, dimethyl ester	**27.36**	**75.97**	**28.26**	0.27	0.22	0.13
D-Limonene	0.10	0.06	0.10	0.04	**8.70**	0.10
Methylene Chloride	0.28	**0.52**	0.19	0.19	0.04	nd
Naphthalene	0.22	0.28	0.28	nd	**0.55**	0.08
Nonanal	**3.82**	**2.55**	**3.40**	**0.66**	**2.17**	0.48
Octanal	0.32	0.16	nd	0.03	nd	nd
Pentanedioic acid, dimethyl ester	**4.68**	**7.89**	**6.36**	nd	nd	nd
Phenol	**0.89**	**1.41**	**3.41**	**1.34**	**0.63**	nd
α-Pinene	0.10	nd	nd	nd	**1.88**	nd
Propanoic acid, 2-methyl, 3-hydroxy-2,4	0.37	**1.21**	**18.74**	**1.09**	**16.08**	**0.72**
2-Propanol, 1-methoxy-	**1.98**	**2.04**	**1.86**	nd	nd	nd
Propylene Glycol	nd	nd	nd	nd	**>80**[d]	nd
Styrene	nd	nd	nd	nd	0.05	nd
α-Terpineol	**0.70**	0.19	0.29	0.12	0.47	nd
Tetradecane	0.12	**0.73**	**0.98**	0.49	0.40	**4.47**
Toluene	**0.82**	**0.62**	**1.17**	0.35	**2.33**	nd
TXIB isomer[e]	0.18	0.11	0.45	0.12	**0.57**	0.09
TXIB[e]	0.18	**1.39**	**9.72**	**0.85**	**9.32**	0.17
unknown phthalate	0.03	nd	nd	nd	nd	nd
m/p-Xylene	0.08	0.07	0.27	nd	0.16	nd
o-Xylene	0.08	0.07	0.22	nd	0.20	nd

[a] Approximate limit of quantification (LOQ) value for the chamber testing was 0.5 ug/m^3. All data are listed for comparison but values above the LOQ are listed in bold text; [b] Italicized chemicals are reported as toluene equivalents; [c] An "nd" means the value was not detected or was below the blank subtract; [d] Concentration is beyond the linear range of the calibration curve and/or instrument response; [e] TXIB is 2,2,4-Trimethyl-1,3-pentanediol di-isobutyrate

Table 3. Standard Emission Factors (μg m^{-2} h^{-1}) for PBC materials determined after 7-days conditioning

	Material Description				
	Old Wood		New Wood		DryWall
Chemical Name	Old Polish	New Polish	No Polish	New Polish	Painted
Formaldehyde	**21.59**[a]	**9.75**	**104.63**	**116.82**[b]	**10.05**
Acetone	nd[c]	nd	nd	nd	0.14
Benzaldehyde	0.10	0.14	0.88	0.45	**7.62**
Benzyl Alcohol[d]	0.15	0.26	**23.14**	**1.96**	**>220**[e]
1-Butanol	0.56	**2.68**	**2.80**	**2.27**	**2.11**
2-Butanol	0.58	1.64	**4.05**	**4.18**	0.50
2-Butoxyethanol	nd	0.77	0.72	0.34	0.67
n-Butyl Laurate	nd	1.37	0.40	0.13	0.99
3-Carene	0.11	nd	nd	nd	20.56
Decamethylcyclopentasiloxane	0.19	0.14	0.11	0.27	0.60
Decanal	**2.10**	0.66	0.65	0.18	**3.18**
1,4-Dichlorobenzene	0.18	nd	nd	nd	1.46
Diethylphthalate	0.02	0.23	0.53	0.27	0.32
Dodecanoic acid, 1-methylethyl ester	nd	0.73	1.27	0.30	nd
Ethanol, 2-(2-butoxyethoxy)-	nd	nd	**10.61**	0.85	**1.83**
Ethylbenzene	nd	nd	0.12	0.12	nd
Hexanal	0.43	0.13	0.47	0.48	0.61
Hexanedioic acid, dimethyl ester	nd	**112.66**	**39.95**	**5.41**	0.54
d-Limonene	0.13	nd	nd	nd	6.92
Methylene Chloride	0.23	**1.35**	0.49	0.43	0.05
Naphthalene	nd	0.06	0.05	0.05	0.42
Nonanal	**3.64**	0.77	0.38	nd	**5.34**
Octanal	0.23	0.11	0.25	0.18	0.37
Pentanedioic acid, dimethyl ester	nd	**6.67**	**4.08**	0.28	nd
Phenol	0.10	0.86	**1.85**	0.48	0.66
Propanoic acid, 2-methyl, 3-hydroxy-2,4	nd	**1.80**	**30.82**	**11.29**	**19.59**
2-Propanol, 1-methoxy-	nd	**2.96**	**4.63**	**4.30**	nd
Propylene Glycol	nd	nd	nd	nd	**>220**[e]
α-Terpineol	0.21	0.18	0.24	nd	0.22
Tetradecane	0.09	0.14	0.18	0.08	0.41
Toluene	nd	**2.06**	0.69	0.66	nd
TXIB isomer[f]	0.11	0.25	0.91	0.35	0.93
TXIB[e]	nd	0.27	**12.45**	**3.99**	**8.74**
m/p-Xylene	nd	nd	0.58	0.58	nd
o-Xylene	nd	nd	0.413	0.41	nd

[a] Approximate limit of quantification (LOQ) value for the emission testing is 1.7 ug/m^2/h. All data are listed for comparison but values above the LOQ are listed in bold text; [b] Values for formaldehyde, acetaldehyde and acetone for the new wood with new polish are reported for after 14 days of conditioning; [c] An "nd" means the value was not detected or was below the blank subtract; [d] Italicized chemicals are reported as toluene equivalents; [e] Concentration is beyond the linear range of the calibration curve and/or instrument response; [f] TXIB is 2,2,4-Trimethyl-1,3-pentanediol di-isobutyrate

Table 4. Building specific parameters used to estimate room air concentrations

Description of parameter	units	Third Floor	Fifth Floor
Estimated floor area	ft^2	7200	7200
Assumed ceiling height	ft	9	9
Absolute volume	m^3	1835	1835
Ventilation (maximum)	m^3/h	1699	2854
ACH[a] (range)	1/h	0.5 - 1.02	0.9 - 1.72
Area of new wood with new polish	m^2	46	18
Area of old wood with new or old polished	m^2	2240	906
Area of drywall	m^2	910	1106
Loading factor new wood with new polish	m^2/m^3	0.025	0.010
Loading factor old wood with new or old polished	m^2/m^3	1.22	0.49
Loading factor drywall	m^2/m^3	0.50	0.60

[a] air change rate adjusted assuming a factor of 0.9 for volume of inaccessible space in room. Maximum values provided for PBC and assumption made of 50% minimum flow in demand response mode.

Table 5. Comparison of estimated to measured formaldehyde in PBC

Material specific contribution to estimated concentration	units	Third Floor	Fifth Floor
New wood with new polish	μg/m^3	3 - 6	1
Old wood with new or old polish	μg/m^3	19 - 37	4 – 9
Drywall	μg/m^3	5 – 10	4 – 7
Range of total estimated concentration	μg/m^3	26 - 53	9 – 17
Measured values on each floor[a]	μg/m^3	20, 27, 29, 30	20, 25, 27, 29

[a] Measured values reported in [2]

Figure 1. Example of prepared material samples installed in conditioning chambers prior to testing. Chambers are shown with lids removed.

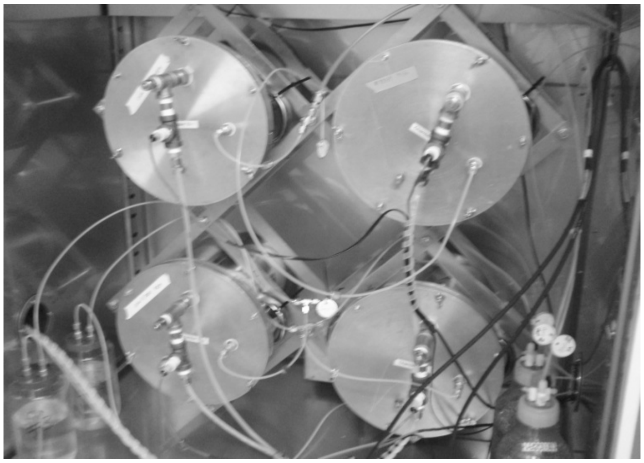

Figure 2. Photograph of emission chambers housed inside controlled environment oven.

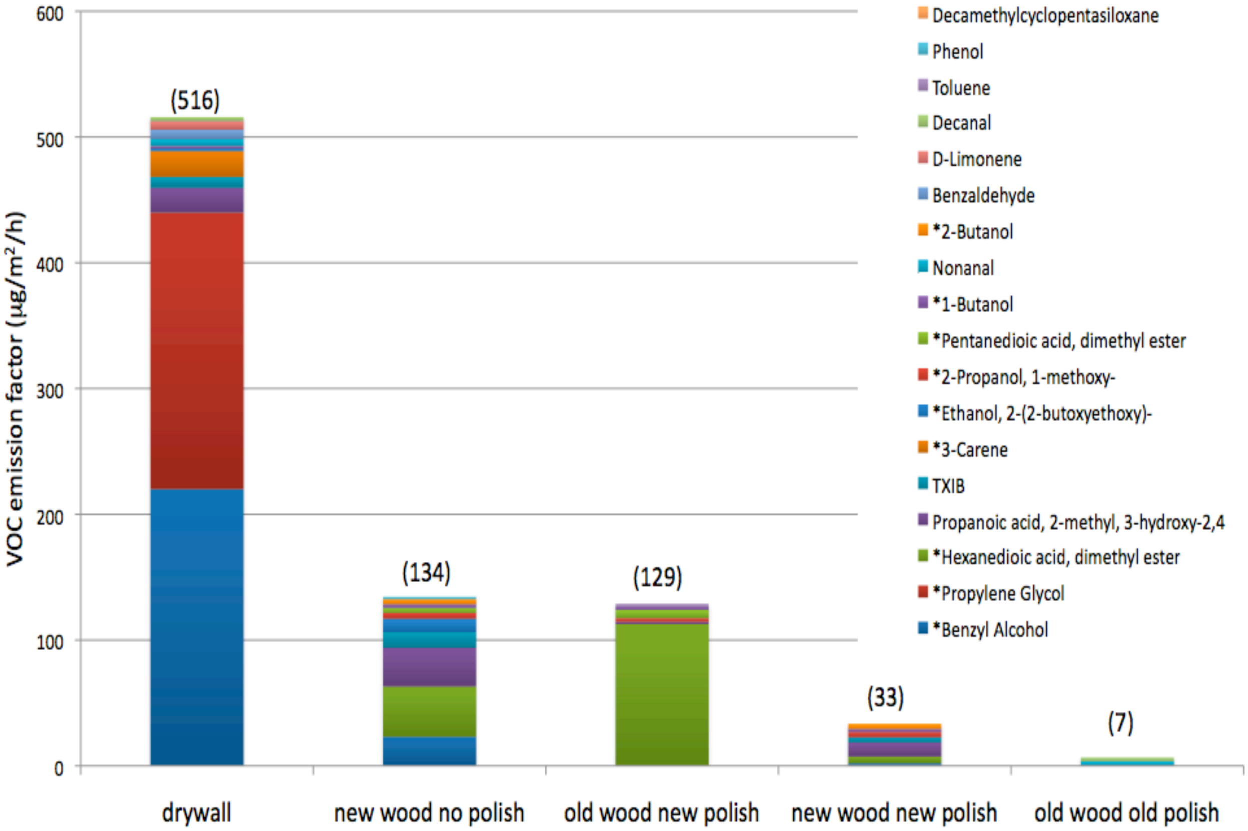

Figure 3. Total VOC emission factors as determined by the methods described in this report (listed in parenthesis above each column) for each material. The legend for the stacked columns is presented in order of decreasing contribution to the total emission stream from bottom to top. The results for formaldehyde are listed separately (see Figure 4) and are not included in this chart.

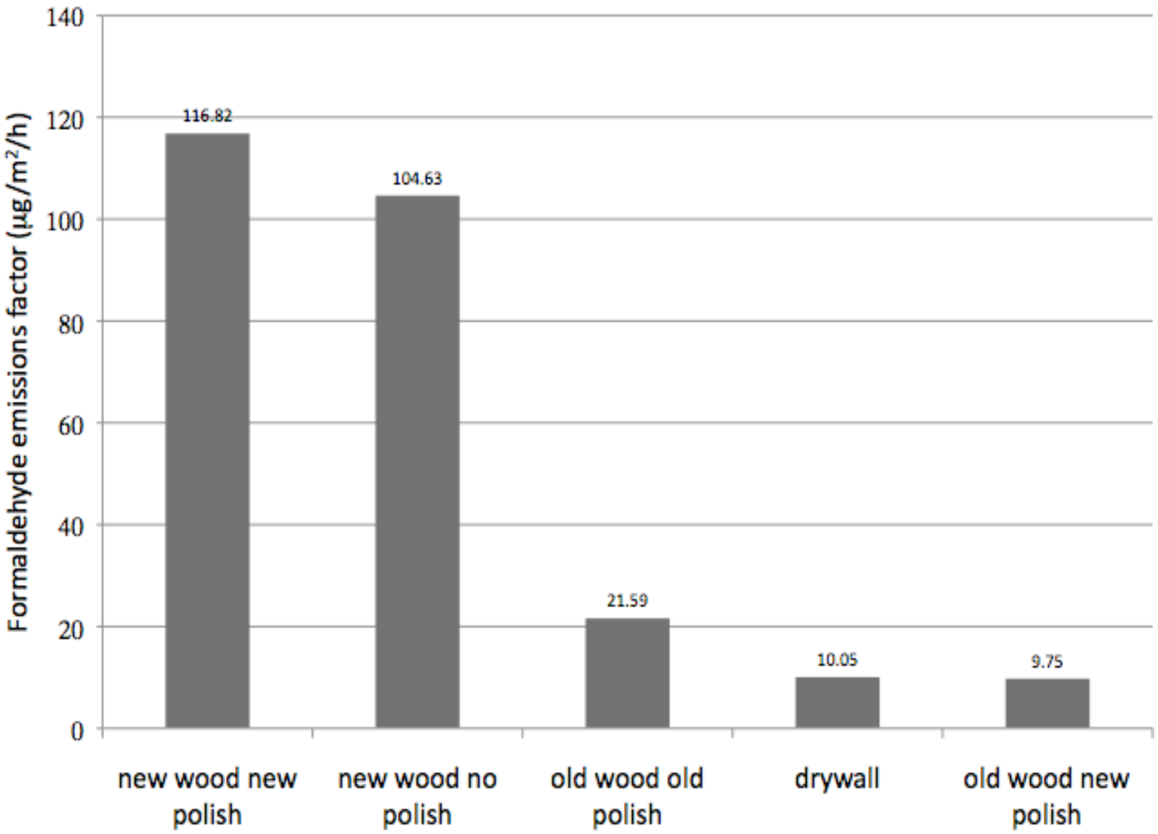

Figure 4. Comparison of formaldehyde emission from the different wall covering materials showing that the new wood is the primary source of formaldehyde and the use of polish does not significantly affect the measured emission factors. Actual values of the emission factors are listed above the column. New wood with new polish was aged 15 days while the other materials were aged 7 days.

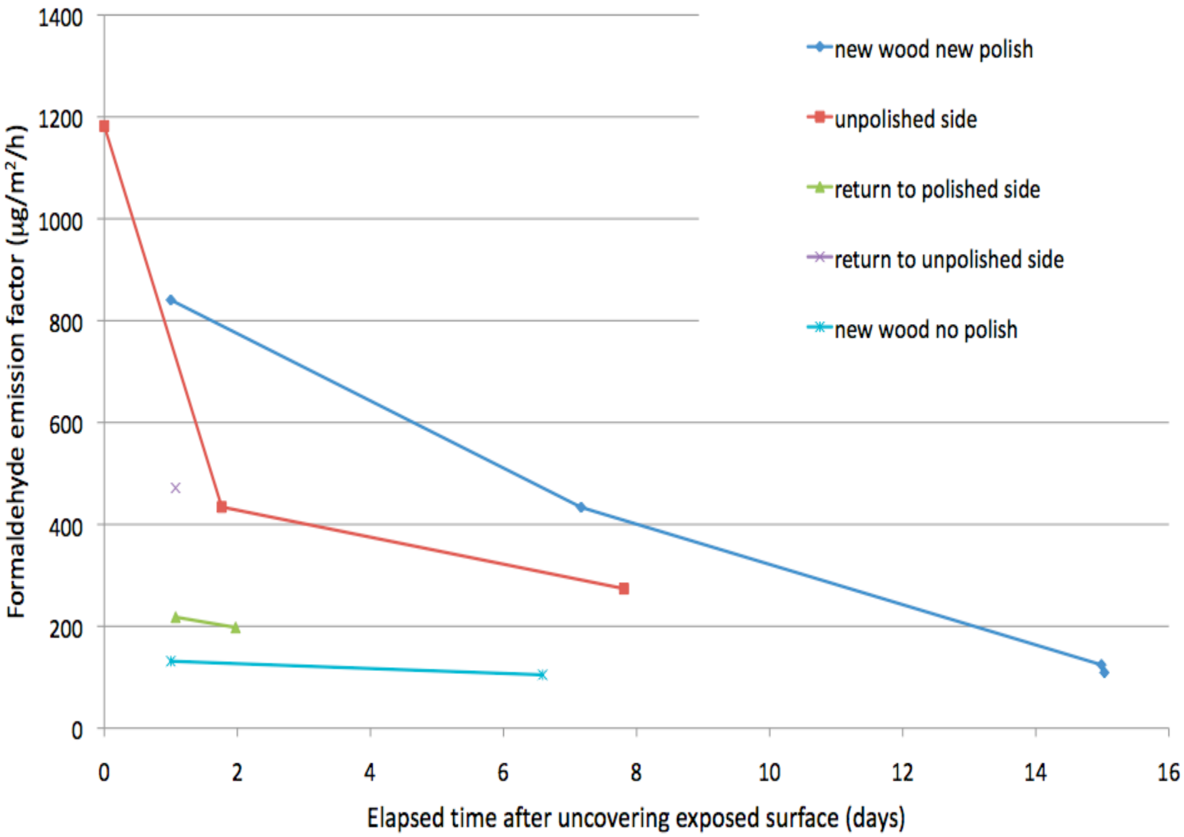

Figure 5. Aging of formaldehyde emissions for polished and unfinished surface of new wood compared to the emissions from the new wood sample with no applied polish. The experiments were run in the order 1) new wood new polish (diamonds) and new wood no polish (asterisk); 2) unpolished side (squares); 3) return to polished side of new wood new polish (triangle); 4) return to unpolished side (cross). During conditioning and testing of the polished side, the unpolished side was covered and visa versa.