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IMPLEMENTATION OF VOC SOURCE REDUCTION PRACTICES IN A MANUFACTURED HOUSE AND IN SCHOOL CLASSROOMS

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ABSTRACT
Detailed studies of a new manufactured house and four new industrialized relocatable school classrooms were conducted to determine the emission sources of formaldehyde and other VOCs and to identify and implement source reduction practices. Procedures were developed to generate VOC emission factors that allowed reasonably accurate predictions of indoor air VOC concentrations. Based on the identified sources of formaldehyde and other aldehydes, practices were developed to reduce the concentrations of these compounds in new house construction. An alternate ceiling panel reduced formaldehyde concentrations in the classrooms. Overall, the classrooms had relatively low VOC concentrations.

INDEX TERMS
VOCs, Formaldehyde, Source reduction, Manufactured houses, School classrooms

INTRODUCTION
Indoor exposures to toxic volatile organic compounds (VOCs) are of obvious concern. In the U.S., schools have become a focus of complaints regarding children's potential exposures to chemical and biological contaminants including formaldehyde. Odorous VOCs also can adversely affect people's acceptance of indoor environments. In new residences, formaldehyde and odorous aldehydes were among the most prevalent and predominate VOCs (Hodgson et al., 2000). Much less is known about the composition and concentrations of VOCs of concern in new schools. For VOCs with material sources, an efficient way to reduce occupant exposures is to eliminate or modify significant sources. Studies in which we collaborated with a manufactured housing company and a relocatable (RC) classroom manufacturer to implement VOC source identification and reduction practices are reported. The objective of the house study was to identify and verify the major sources of formaldehyde and other VOCs with emphasis on odorous compounds (Hodgson et al., In press). The objective of the school study was to construct two new classrooms using low-emitting interior materials and to compare concentrations of toxic VOCs over time in these classrooms with concentrations in two new standard classrooms serving as controls (Hodgson et al., 2001).

METHODS
Procedures were developed to quantify and assess the emissions of VOCs from interior materials. Specimens of materials of known history were obtained from the building production facilities or from the material manufacturers and then tested for VOC emissions using small-scale chambers following standard guidance (ASTM, 1997). Our method employed specimen conditioning (19 ± 4 days for the house and reduced to 10 days for the schools to improve practicality) prior to a 4-day test with samples collected at the end of this period to generate VOC emission factors (µg m^{-2} h^{-1}) approximating those in a building during early occupancy. Our recommended conditioning and testing methods are summarized

in Table 1. Chambers of different sizes may be used; however, the specimen surface area to airflow rate ratio should be kept within a range appropriate for materials covering large areas such as floors and ceilings to establish realistic chamber VOC concentrations.

Table 1. Recommended parameters for testing materials for VOC emissions.

Parameter	Units	Conditioning	Test Period
Temperature	^oC	23 ± 2	23 ± 1
Relative humidity	%RH	50 ± 10	50 ± 5
Chamber volume	m^3	0.01 - 0.08	0.01 - 0.08
Specimen area	m^2	~0.02	~0.02
Area/Flow rate ratio	$m^2 / m^3 h^{-1}$	0.25 - 0.45	0.25 - 0.45
Duration	h	≥240	96

Since previously we had identified the predominant VOCs in new manufactured houses from the same facility in Florida (Hodgson et al., 2000), the house study focused on wood and wood products, which were the most likely sources of formaldehyde and odorous aldehydes. These materials included cabinetry components, interior doors and the plywood subfloor. Emission rates of toxic and odorous VOCs attributable to each major material to be used in the test house were calculated from the measured emission factors and the quantity of material installed in the house. These emission rates were summed by compound to predict whole-house emission rates. Indoor and outdoor aldehyde and VOC measurements were made three months after the house was installed at a sales center. The house ventilation rate was at steady-state conditions and was quantified concurrently by SF_6 tracer gas decay. Whole-house emission rates were derived by steady-state mass balance from the concentrations and the house ventilation rate and volume.

Table 2. Toxic chemicals of concern in California.

California Regulatory Lists of Toxic Chemicals	www.URL
Air Toxics Hot Spots Program Risk Assessment Guidelines; Chemicals with Established Noncancer Chronic Reference Exposure Levels (RELs)	oehha.org/air/ chronic_rels/
Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65); Chemicals Known to the State to Cause Cancer or Reproductive Toxicity	oehha.org/prop 65/prop65_list/
Substances Identified as Toxic Air Contaminants (TACs) by the Air Resources Board (includes all U.S. EPA Hazardous Air Pollutants)	arb.ca.gov/ toxics/taclist.htm

Working with a California manufacturer of RC classrooms, a study was conducted to measure VOC emissions from a number of standard and alternate interior finish materials (Hodgson et al., 2001). Alternate carpets, wall panels and ceiling panels were selected for use in the construction of two modified classrooms based on these results and considerations of cost, performance and maintenance. Emphasis was placed on reducing indoor concentrations of VOCs that appear on California regulatory lists of toxic chemicals (Table 2). VOC concentrations were estimated for these classrooms and two standard classrooms based on the measured emission factors, material quantities, building volumes, and design ventilation rates based on expected occupancy. The four classrooms subsequently were constructed for a field study. For a case-crossover design, each classroom was equipped with a standard HVAC system and an advanced system employing indirect/direct evaporative cooling (IDEC) to provide continuous ventilation of at least 7 L s^{-1} per occupant (Apte et al., 2001). At each of two schools, a modified classroom was sited adjacent to a standard classroom. In the fall semester, integrated school-day indoor and outdoor aldehyde and VOC measurements were made weekly for eight weeks with HVAC systems switched on alternate weeks. Energy and environmental parameters were measured continuously. At the beginning and end of the 8-week period, classroom DEC systems were operated at steady-state conditions during unoccupied hours. Indoor and outdoor aldehyde and VOC concentrations were measured and the ventilation rates were quantified by CO_2 tracer decay. Whole-building emission rates were derived from these data by mass balance.

RESULTS AND DISCUSSION

A large mass and bare (unfinished) surface area of composite wood products were used in the production of the house kitchen, utility and bathroom cabinets (Table 3). The top surfaces of the countertops were finished with laminate. The other composite materials had decorative polyvinyl chloride (PVC) applied to one or more surfaces. The other predominant wood products in the house were the passage doors (molded high-density fiberboard with acrylic finish) and the plywood subfloor under carpeted areas (Table 3). Bare particleboard (PB) and medium density fiberboard (MDF) surfaces had relatively high formaldehyde emission factors. The finished surfaces (laminate and PVC) of these materials had substantially lower emission factors. The installation of a standard carpet and cushion over the plywood had no significant effect on the emission factors of most aldehydes including formaldehyde. The cabinetry materials and passage doors were the largest predicted contributors to formaldehyde whole-house emission rates; the subfloor was the largest predicted source of hexanal, an odorous aldehyde (Table 3).

Table 3. Quantities of composite wood products used in new house and predicted whole-house emission rates of formaldehyde and hexanal from these sources.

Material Description	Mass (kg)	Bare Area (m^2)	Emission Rate ($mg\ h^{-1}$) Formald.	Emission Rate ($mg\ h^{-1}$) Hexanal
PB[a] counter top, underside	155	12.1	1.0	2.7
PB case, 1 side	74	9.2	4.3	--
MDF[b] stile, 1 of 4 sides	72	4.9	1.6	1.2
Hardboard, 1 side	39	11.7	0.1	--
Cabinetry Totals	340	38	7.0	3.9
Passage doors	--	25	3.8	1.1
Plywood subfloor[c]	1,270	111	1.1	18.3

[a]PB = particleboard; [b]MDF = medium-density fiberboard; [c]Area overlain by carpet.

Concentrations of selected VOCs measured in the house at a ventilation rate of 0.28 h^{-1} three months after installation are presented in Table 4 along with a comparison of derived and predicted whole-house emission rates. The formaldehyde concentration was within the range of typical maximum guideline values of 50-100 ppb. The concentrations of many higher molecular weight aldehydes exceeded their odor thresholds (Devos et al, 1990). For 10 of the 14 compounds including formaldehyde, the average predicted rates were within a factor of ±2 of the derived rates, suggesting that many of the sources of these compounds were correctly accounted for.

Concentrations of formaldehyde and odorous aldehydes can be reduced in new manufactured house construction by several simple practices directed at cabinet construction and other sources (Table 5). A PVC-coated door of identical design was found to reduce formaldehyde emissions from this source to a negligible level (<0.1 mg h^{-1}). Overlaying plywood with a carpet cushion with an integral spill barrier or a sheet barrier material was partially effective for reducing aldehyde emissions. However, the potential for such materials to create moisture-related problems in hot-humid climates requires investigation.

Table 4. Concentrations and emission rates of terpenes and aldehydes in new house.

Compound	In-Out Conc (ppb)	Odor Threshold[a] (ppb)	Derived ER[b] (mg h^{-1})	Predicted ER[c] (mg h^{-1})	Pred/Deriv w/in 2 x? Y/N[d]
α-Pinene	42	690	25 ± 4	12.9-31	Y
β-Pinene	13.3	--	8.1 ± 1.3	3.4-7.8	Y
d-Limonene	7.2	44	4.4 ± 0.7	3.3-12.6	Y
Formaldehyde	74	870	9.9 ±1.6	11.7-12.2	Y
Acetaldehyde	21	186	4.2 ±0.7	2.0-3.0	Y
Pentanal	21	6.0	8.0 ± 1.3	3.7-4.1	N
Hexanal	65	13.8	29 ± 5	22-24	Y
2-Furaldehyde	3.9	780	1.69 ± 0.27	0.94	Y
Heptanal	5.3	4.8	2.7 ± 0.4	0.53-0.59	N
2-Heptenal	3.0	13.5/6.0[e]	1.51 ± 0.24	0.61-0.69	N
Benzaldehyde	3.1	42	1.46 ± 0.23	1.06	Y
Octanal	8.2	1.3	4.7 ± 0.7	1.19-1.29	N
2-Octenal	3.7	2.0/0.7[e]	2.1 ± 0.3	1.52-1.69	Y
Nonanal	7.0	2.2	4.5 ± 0.7	2.8-3.0	Y

[a]Devos et al., 1990; [b]Emission rates (ERs) ± 1 stdev. derived from concentrations and house parameters; [c]Predicted whole-house ERs are sums of ERs for wood product sources; [d]Y/N = Yes/No, predicted ER is within factor of two of calculated ER; [e]*cis* isomers of 2-heptanal and 2-octenal have lower odor thresholds than *trans* isomers.

Table 5. 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 alternate low-formaldehyde emitting passage doors
6	Apply barrier material over plywood subfloor in carpeted areas (see caution in text)

The laboratory study of RC classroom materials showed that the standard and alternate carpets generally were not significant sources of VOCs of concern. Also, glue-down carpet systems reduced the emissions of formaldehyde from the subfloor. Fiberglass ceiling panels were identified as the major formaldehyde source among the standard materials. The emission factor was 32 µg m^{-2} h^{-1}. Two mineral-fiber ceiling panels were tested. One had emissions comparable to the fiberglass material, while the other had no detectable formaldehyde emissions. The classroom walls were entirely covered with tackable panels. Five panel systems were tested. The standard wood fiber panel covered with PVC fabric emitted acetaldehyde, phenol, 2-(2-butoxyethoxy)ethanol, vinyl acetate, 1,24-trimethylbenzene and 1-methyl-2-pyrrolidinone. The selected alternate, which was identical except that the PVC fabric was Teflon coated, was predicted to reduce concentrations of these compounds, while increasing toluene concentrations by ~1 ppb during occupancy.

RC formaldehyde concentrations were higher than predicted by the laboratory study. The formaldehyde emission rates in the four classrooms derived from measurements made at the beginning (pre) and end (post) of the 8-week study are shown in Table 6. At the end, there was an aberrantly high emission rate in RC 4. This was attributed to an as yet to be identified source added to the room during the study. Ignoring this value, the formaldehyde emission rates decreased over the course of the study, and the modified classrooms had lower emission rates than their paired standard control classrooms. Concentrations were predicted for the classrooms based on the average measured IDEC airflow rate for each school. These were higher for School A due to higher occupancy. The predicted values are generally consistent with the measured concentration ranges. The higher concentrations in control classrooms RC 1c and RC 3c occurred during days when their IDEC systems were not operated continuously.

Table 6. Derived formaldehyde emission rates and predicted formaldehyde concentrations in four new classrooms operating with IDEC system. Emission studies were conducted prior to (pre) and after (post) 8 weeks of occupancy. Predictions were made using respective average airflow rates of 850 and 675 $m^3 h^{-1}$ for Schools A and B and are compared to concentrations measured over four weeks of classroom use with IDEC system. Rooms RC 2 and RC 4 had ceiling panels with negligible formaldehyde emissions. Rooms RC 1c and RC 3c are controls.

	Derived Emission rate ($\mu g\ h^{-1}$)		Indoor-Outdoor Concentration (ppb)			
			Predicted		Measured during use	
School, Room	Pre	Post	Pre	Post	Average	Range
School A, RC 1c,	9,900	3,450	9.5	3.3	9.9	3.5 – 19.1
School A, RC 2	7,040	2,660	6.7	2.5	4.1	3.0 – 4.7
School B, RC 3c	3,800	1,310	4.6	1.6	6.1	2.8 – 10.6
School B, RC 4	2,370	26,800*	2.9	32.3	12.1	8.4 – 17.4

*Attributed to unidentified source added after fall semester began.

Table 7 compares the concentrations of toxic VOCs other than formaldehyde in the four classrooms over the four weeks in which the IDEC system was used. Some additional toxic VOCs (not shown) were measured at generally lower concentrations. The concentration ranges for paired modified and control classrooms overlap, with several exceptions. 1-Methyl-2-pyrrolidinone and phenol (School B only) concentrations were lower in the modified classrooms probably due to the use of the alternate wall panel. Caprolactam was highest in one control classroom. The likely source was the Nylon 6 fiber carpet installed in that room, but not included in the laboratory study. Toluene differences were small as predicted.

Table 7. Concentrations of other toxic VOCs in four new classrooms over four weeks of use with IDEC system. Rooms RC 2 and RC 4 are modified; RC 1c and RC 3c are controls.

		Indoor-Outdoor Concentration (ppb)			
	Study	School A		School B	
Compound	Median	RC 1c	RC 2	RC 3c	RC 4
Toluene	0.7	0.2-0.6	0.3-0.7	0.3-1.0	0.5-1.9
2-Propanol	2.6	2.1-6.6	2.4-6.7	2.0-5.0	2.0-5.6
Phenol	1.0	0.8-2.5	0.3-0.8	0.2-1.4	<0.1-1.0
Vinyl acetate	0.1	<0.1-0.2	<0.1	<0.1	0.1-0.4
Acetaldehyde	3.1	0.1-4.7	0.2-1.3	<0.1-2.9	0.4-5.2
2-Butanone	0.3	0.1-0.4	0.1-0.3	<0.1-0.4	0.1-0.4
1-Methyl-2-pyrrolidinone	0.2	0.2-0.5	<0.1	0.2-1.8	<0.1-0.1
Caprolactam	0.2	0.1-0.2	<0.1-0.1	2.3-6.5	0.1-0.3

CONCLUSIONS

The composition and concentrations of VOCs in the manufactured house and the classrooms were substantially different. The house had relatively elevated concentrations of formaldehyde and acetaldehyde and of odorous aldehydes that often exceeded odor thresholds. The school study focused on listed toxic chemicals, but also included the analysis of odorous aldehydes. The concentrations of these compounds were low. The differences between the house and the classrooms largely were due to the much higher ventilation rates and the use of higher quality, fully encapsulated cabinetry and generally less wood products in the classrooms. Although the school data have yet to be fully analyzed, several small improvements in the concentrations of toxic VOCs can probably be attributed to the use of alternate materials. The use of the alternate wall panel had a small impact on the concentrations of several VOCs. The use of a lower emitting ceiling panel probably reduced formaldehyde concentrations.

These studies found that the systematic identification of VOC sources and the implementation of source reduction practices can be effectively implemented in industrialized buildings. As the process was shown to be relatively accurate, manufacturers can be assured that if they test the standard and new materials under consideration, most problematic sources of VOC contamination will be identified and eliminated. Because manufacturers construct large numbers of units, which often incorporate the same interior materials, the costs are not likely to be prohibitive due to economies of scale.

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REFERENCES

Apte MG, Delp WW, Diamond RC, et al. 2001 *Report on HVAC option selections for a relocatable classroom energy and indoor environmental quality field study*, Report no. LBNL-49026, Lawrence Berkeley National Laboratory, Berkeley, CA.

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

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

Hodgson AT, Rudd AF, Beal D, and Chandra S. 2000. Volatile organic compounds concentrations and emission rates in new manufactured and site-built houses, *Indoor Air*10: 178-192.

Hodgson AT, Fisk WJ, Shendell DG and Apte MG. 2001. *Predicted concentrations in new relocatable classrooms of volatile organic compounds emitted from standard and alternate interior finish materials*, Report no. LBNL-48490, Lawrence Berkeley National Laboratory, Berkeley, CA.

Hodgson AT, Beal D, and McIlvaine JER. In press. Sources of formaldehyde, other aldehydes and terpenes in a new manufactured house, *Indoor Air*.