TERPENE EMISSIONS FROM PARTICLEBOARD AND MEDIUM-DENSITY FIBERBOARD PRODUCTS

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ABSTRACT

Indoor air quality problems resulting from emission of volatile organic compounds (VOCs) have become an issue of increasing concern. Factors known to affect VOC levels in indoor air include: ventilation rate, occupant activities, and emissions from building and furnishing materials. In this research, VOC emissions from particleboard and medium density fiberboard (MDF) were measured in small stainless steel chambers (53 L) during a 4-day period. A protocol was developed to obtain new and representative samples and to minimize contamination of the samples during collection, preparation, and shipment to the laboratory. Samples were collected from 53 of the 61 U.S. mills that produce particleboard and MDF. Each mill identified the predominant tree species used to manufacture the panels. The laboratory tests were conducted at 45 percent relative humidity and used a gas chromatograph and a mass selective detector to identify and quantify VOC compounds. The predominant compounds identified in emissions from the particleboard and MDF samples were terpenes and aldehydes. Small straight-chain alcohols and ketones were also found. This study describes the terpene emission data. Quantified terpenes included α– and β-pinene, camphene, 3-carene, *p*-cymene, limonene, and borneol. Terpene emissions accounted for between 7 and 21 percent of the total VOC emissions, calculated as α-pinene. The highest terpene emissions were observed from particleboard samples manufactured from pines other than southern pine. For particleboard, terpene emissions were largely related to the extractive content of the wood species. The terpenes were almost completely absent in emissions from MDF samples, which indicates that differences in the manufacturing of MDF compared with the manufacturing of particleboard may have considerably affected emissions. After 4 days, the terpene emissions from all particleboard samples decreased to between 20 and 70 percent of their initial values.

During the past several decades, air quality in homes and office buildings has become a matter of increasing concern. Indoor air concentrations of volatile organic compounds (VOCs) are often significantly higher than outside due to VOC emissions from building materials, furnishings, and occupant's activities. This problem was exacerbated following the energy crisis in the 1970s as homeowners and builders improved the energy efficiency of their buildings by decreasing air exchange rates. Adverse health effects associated with moderate and high VOC concentrations include: eye and respiratory irritation (including asthma), irritability, inability to concentrate, and sleepiness. Trätek, the Swedish Institute of Wood Technology Research (Stockholm, Sweden), estimates that 7 to 10 percent of the Swedish population has suffered ill health as a direct result of poor indoor air quality, caused in part by VOCs emitted by building materials and furnishings (2).

Because of increased emphasis on indoor air quality, accurate information is needed regarding the amounts and types of VOCs emitted from building materials, furnishings, cleaning products, and other materials found or used in the indoor environment. Such information will allow building occupants, product manufacturers, building designers and contractors, and regulatory and public health agencies to make informed decisions about the products they use and recommend. Increasingly, some product manufacturers are advertising "low VOC" materials or materials suitable for use by people with chemical sensitivities. Building designers and contractors are now being asked to certify that new buildings will meet indoor air quality requirements set by building owners. Accurate emissions information is needed to decide which materials will best meet those requirements while fulfilling structural and aesthetic needs.

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The Washington State East Campus Plus project (6) provides an example of how these requirements affect planning. During the design and construction of four state office buildings, indoor air quality specifications were established that limited VOC emissions from building materials and furnishings. To ensure that these specifications would be met, many of the building and furnishing materials were tested for VOC emissions prior to installation. For example, specified office furniture systems could emit no more than 0.05 ppm formaldehyde and 0.50 ppm total VOCs.

In the United States, there are no federal regulations to govern VOC concentrations in indoor air. However, regulatory agencies such as the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA) have shown an interest in ensuring that people are not adversely affected by indoor air in their homes and offices. Development of indoor air VOC standards is complicated by the following factors: 1) correlations between product emissions and indoor concentrations are not straightforward; 2) many VOCs result from occupant activities, including smoking, use of cleaning products or perfumes, and cooking; and 3) detection of specific VOCs at low concentrations does not indicate whether or not they will have long-term health effects.

Composite wood products such as particleboard, hardwood plywood, and medium density fiberboard (MDF) are widely used in indoor products (i.e., subflooring, door cores, cabinets, paneling, and furniture.) In 1994, combined shipments of particleboard and MDF in the United States totaled almost 5.4×10^8 m^2 (19-mm basis) (15). With the broad use of composite wood products in modem homes and offices, there are concerns that emissions from these products could have a significant impact on indoor air quality.

Composite wood products are fairly simple combinations of wood and water-based adhesives. The adhesives are composed of either urea-formaldehyde (UF) or phenol-formaldehyde (PF) resin, inorganic components that act as catalysts, and other minor components (i.e., wax.) Increasingly, polymeric methylene diisocyanate (pMDI) is used to bond oriented strandboard (OSB) products. However, few particleboard and MDF products are bonded with pMDI, and these products are for specialized purposes. Emissions of VOCs potentially can arise from each of the materials that compose a panel, but attention, until recently, has been on emissions of formaldehyde from the UF resins used to bind particleboard, MDF, and hardwood plywood. The focus has recently shifted to a variety of VOCs.

Earlier research (5, 13, 16, 17) identified a wide variety of VOCs including acetone, benzene, hexanal, and toluene emitted from composite wood products. Some of these compounds have not previously been associated with wood products, and there is no ready explanation for their presence. Previous studies used various types of chambers, different material loading ratios, a range of air exchange rates, a variety of methods for sample collection and storage, and different analytical procedures. These differences make comparison and interpretation of the published data difficult, if not impossible. The identification and quantification of emissions from wood products (and other materials) should use standardized methods as called for by many investigators in the United States and abroad.

To answer questions about VOC emissions from wood composite products, we undertook a study of emissions from unfinished particleboard and MDF produced in the United States. A similar study of Canadian-produced products has been completed by researchers at Forintek Canada (A.O. Barry, 1995, unpublished data). In our study, small, stainless steel chambers were used to house small samples of wood products under controlled environmental conditions. Wood samples were collected directly from the mills using a sampling protocol developed by USDA Forest Service, Forest Products Laboratory (FPL) researchers, thus decreasing the possibility of postmanufacture contamination. Samples were collected and evaluated from 53 of the 61 mills in the United States that manufacture particleboard and MDF. Most mills not included in this study either produce specialized products or use materials that are atypical of the particleboard and MDF industries. This study details the evaluation of terpene emissions from these particleboard and MDF products.

EXPERIMENTAL PROCEDURE

SAMPLE COLLECTION FROM MILLS

Samples of particleboard and MDF were collected by three National Particleboard Association (NPA) employees during routine visits to the mills. (In March 1997, the NPA and the Canadian Particleboard Association joined together to form the Composite Panel Association (CPA)). Sample collection kits were provided by FPL, and explicit sample handling instructions were given to each of the sampling personnel. To prevent exposure to or loss of VOCs during shipping, 300- by 300-mm (12- by 12-in.) panel samples were sandwiched between two pieces of the same panel, wrapped in aluminum foil, double-bagged in polyethylene zipper bags, and placed inside a mailing envelope prior to shipping. Information about the product type, predominant wood species, additives used, and manufacturing conditions was recorded at the time of panel sample collection. General information about each panel, including resin type and wood species, was provided to FPL along with the panel samples. Sampling was blind in that FPL researchers were not given information identifying the individual mill or manufacturer of each sample.

Panel samples were collected at the mills from March to June of 1997. Upon receipt at FPL, the samples were logged and placed in storage at 2°C until testing commenced. A total of 57 particleboard and MDF panel samples were collected, including duplicates from four mills. All panels were bonded with UF resin, and the products were divided into nine product-species groupings based on manufacturer reports of predominant species groups used at the mills: southern pine particleboard (22 samples), other pine particleboard (8 samples), Douglas-fir particleboard (4 samples), hardwood particleboard (4 samples), other particleboard (1 sample), southern pine MDF (6 samples), other pine MDF (5 samples), hardwood MDF (5 samples), and other MDF (2 samples). Duplicate panel samples, included in the numbers above, were provided for southern pine particleboard, hardwood particleboard, southern pine MDF, and other pine MDF.

LABORATORY SAMPLING SCHEDULE

The testing series was a 5-day cycle, consisting of 1 day of blank runs in the chamber and 4 days of collecting and

TABLE 1. - Summary of chamber conditions during testing.

Parameter	Value
Chamber volume	0.053 m^3
Chamber air flow	0.001 m^3/minute (1.13 air changes/hr.)
Temperature	23±1°C(73±1°F)
Chamber humidity	45% ± 5%
Sample area	0.021 m^2
Loading ratio	0.40 m^2/m^3
GC sample volume	315 mL

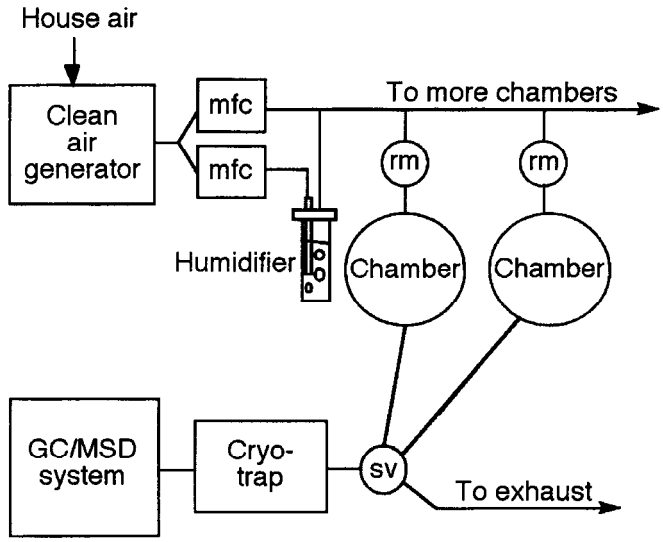

Figure 1. – Automated volatile organic compound analysis system (mfc = mass flow controller; rm = rotameter; sv = sampling valve).

analyzing air samples. On the first day, prior to putting specimens into the chambers, blank runs were performed for each of the empty chambers while clean, humidified air flowed through the chamber at a rate of 1 L/minute. Wood panel samples were removed from the cold room, and a 102- by 102-mm test specimen was cut from each of the center panels, discarding the outer 25.4 mm from each sample panel and the outer panels used during shipping. To minimize edge emissions, specimens were edge-sealed by brushing the edges with two coats of a saturated solution of sodium silicate and left to dry overnight in a room maintained at 23°C (73°F) and 43 percent relative humidity (RH).

The specimens were then placed into nine of the chambers, leaving one chamber empty to serve as a control, and the time was recorded. The chambers were closed, and clean humidified air flowed through the chambers for the next 4 days.

On days 1, 2, and 3 of the 4-day specimen testing (at approximately 24, 48, and 72 hr.), air samples were drawn from each chamber and analyzed for VOCs. The air sampling and analysis procedures are described in the following sections. In addition, on day 2 (48 hr.), air samples were collected on 2,4-dinitrophenylhydrazine cartridges for aldehyde and ketone analysis. This information will be reported in a subsequent publication.

CHAMBER SYSTEM

Figure 1 depicts the experimental chamber system (3,4), which was constructed in accordance with ASTM D5116-90 (1). The 10 electropolished stainless steel test chambers had a nominal volume of 53 L and were located within a conditioned room maintained at 23°C (73°F). Clean, humidified air was metered into each chamber at 1.0 L/minute, providing 1.13 air exchanges per hour to each chamber. The inlet and outlet ports consisted of tubes that extended to within 2 cm of the bottom of the chamber. Holes were distributed along the length of the tubes to assure adequate mixing of the inlet air with chamber air and to assure that air samples collected at the chamber outlet were an average of the chamber air.

A clean air supply to the chambers was generated by passing house-compressed air through sorbent towers and a catalytic oxidation unit. A portion of the dry, purified air was humidified using a temperature-controlled impinger containing hydrocarbon-free water and blended with dry air to produce 45 ± 5 percent RH. The humidified airstream was then distributed to the chambers.

Chamber outlets led to a rotary switching valve that allowed sequential sampling of air in the chambers without having to connect or disconnect tubing. All materials in contact with the sample air were constructed of stainless steel, glass, or Teflon. Chamber conditions during testing are summarized in **Table 1.**

VOLATILE ORGANIC COMPOUND COLLECTION AND ANALYSIS

When a particular chamber was selected using the sampling valve, 315 mL of air from that chamber was passed through a cryoconcentrator (CDS Analytical, Peakmaster EV, Oxford, Pa.) at -100°C where VOCs condensed out of the air sample. Subsequently, the cryoconcentrator trap was heated to 150°C for 5 minutes to transfer the VOCs to the gas chromatograph (GC) (Hewlett Packard 5890 II, Palo Alto, Calif., with electronic pressure control). The VOCs were cryofocussed at the head of the GC column at -100°C. The column head was then heated to 150°C within ~ 15 seconds and held at that temperature for 3 minutes to inject the VOCs into the GC.

During separation of the VOCs, the GC column (EC-5, 30 m by 0.25 mm, 25-µm film thickness, Alltech Associates, Inc., Deerfield, Ill.) was held at -20°C for 5 minutes, then heated to 120°C at a rate of 10°C/minute, and finally held at 120°C for 5 minutes. This program achieved adequate separation of the compounds expected from wood products. After the compound passed through the GC, a mass selective detector (MSD) (Hewlett Packard 5972) at the GC column outlet was used to detect the various VOCs.

The following target compounds were based on a review of the literature (5,9, 14,16,17,19) and include the major terpenes, aldehydes, and alcohols that have been associated with wood products:

acetaldehyde	heptanal	pentanal
acetic acid	heptane	pentane
acetone	2-heptanone	1-pentanol
benzaldehyde	3-heptanone	α-pinene
benzene	hexanal	β-pinene
borneol	isopropanol	toluene
butanal	limonene	*m*-xylene
2-butanone	nonanal	*o*-xylene

camphene	octanal	*p*-xylene
3-carene	octane	
p-cymene	1-octenal	

Acetaldehyde and acetone were detected and quantified by using 2,4-dinitrophenyl-hydrazine with subsequent HPLC analysis. They are not included in the TVOC calculations presented in this paper.

The VOCs were identified and quantified using retention time and a spectral library developed for each target compound. Nontarget compounds were identified by comparison with a standard mass spectral library (12); however, concentrations were not quantified.

GC-MSD CALIBRATION

Calibration curves for the target compounds were constructed using standards prepared from neat VOCs in pentane solutions, direct injections into the GC injection port, and cryofocussing on the GC column. Quantitation was based on the concentrations of particular ions representative of the compounds being analyzed. Careful selection of the ions allowed compounds with close GC elution times to be quantified without interfering with one another. Limits of detection for all terpenes were between 0.06 and 0.14 $\mu g/m^3$. Based on replicate samples, reproducibility of VOC measurements was typically 10 to 25 percent. Target compounds were not detected in blank tests.

RESULTS AND DISCUSSION

Among the target compounds, the predominant VOCs emitted from the particleboard and MDF samples were the terpenoid compounds and several straight-chain aldehydes, including pentanal, hexanal, and *t*-2-octenal. Several nontarget compounds, including heptanol, 2-pentylfuran, camphor, fenchone, and fenchol, were identified in numerous samples. Aromatic and halogenated compounds, which have been reported by other researchers (5,16), were not detected in any of the samples.

The 48-hour (day 2) concentrations of monoterpenes from the particleboard and MDF samples are summarized in **Tables 2** through **4.** Emissions from samples after 48 hours in the chamber were chosen for detailed analysis, so that results could later be compared with the aldehyde and ketone data collected on 2,4-dinitrophenylhydrazine cartridges. Results from all days showed similar patterns in differences between the species groupings and product types. In the 48-hour tests, the target terpenes accounted for 7 to 21 percent of the total VOC emissions (calculated as α-pinene) from the particleboard samples. There were significant differences among the particleboard samples in the types of terpenes emitted. Terpenes were almost entirely absent from the MDF samples.

TABLE 2. – Average 48-hour emission factors for monoterpenes, as measured by GC-MSD, ,for particleboard samples listed by manufacturer-designated predominant species group.

Detected volatile organic compound	Average 48-hour emission factors				
	Southern pine (22)[a]	Pine (8)	Hardwood (3)	Douglas-fir (4)	Other (2)
	($\mu g\ m^{-2}h^{-1}$)				
α-pinene	42	42	9	11	51
Camphene	3	3	ND[b]	ND	2
β-pinene	19	72	3	1	27
3-carene	ND	78	3	2	ND
p-cymene	6	28	ND	4	3
Limonene	9	50	ND	9	7
Fenchone	NQ[c]	NQ	ND	ND	ND
Fenchol	NQ	NQ	ND	ND	ND
Camphor	NQ	NQ	ND	ND	ND
Borneol	16	11	ND	4	9
Total terpenes	95	284	15	31	99
TVOC[d]	1,146	1,340	659	159	788
Terpenes in TVOC (%)	8	21	2	19	13

[a] Values in parentheses indicate number of samples.
[b] ND = not detected in any of the samples.
[c] NQ = detected in some samples, but not quantified.
[d] TVOC = sum of compounds quantified as α-pinene based on their total-ion-current areas, It does not include compounds that were not quantified by GC-MSD, including formaldehyde, acetaldehyde, and acetone.

***TABLE 3.** – Median, minimum, and maximum emission factors for emissions from particleboard after 48 hours in the test chamber:*

Detected terpene	Southern pine (22)[a]			Pine (8)			Hardwood (3)			Douglas-fir (4)		
	Median[b]	Low	High	Median	Low[c]	High[c]	Median	Low	High	Median	Low	High[c]
	($\mu g\ m^{-2}h^{-1}$)											
α-pinene	40 (22)	11	152	23 (8)	6	209	11 (3)	6	11	8 (3)	0	34
Camphene	3 (16)	0	6	2 (4)	0	14	0 (0)	0	0	0 (0)	0	0
β-pinene	17 (22)	3	60	26 (7)	0	434	3 (2)	0	3	4 (1)	0	6
3-carene	0 (0)	0	0	48 (8)	9	286	3 (2)	0	3	8 (1)	0	9
p-cymene	6 (22)	0	14	24 (8)	3	71	0 (0)	0	0	8 (2)	0	17
Limonene	14 (15)	0	23	31 (8)	6	168	0 (0)	0	0	38 (1)	0	37
Borneo1	17 (22)	3	40	12 (8)	6	17	0 (0)	0	0	4 (3)	0	11
TVOC[d]	1,138 (22)	96	653	1,060 (8)	615	3,252	323 (3)	226	1,450	96 (4)	52	395

[a] Values in parentheses indicate number of samples.
[b] Median of nonzero values. Numbers in parentheses are the total number of samples that had detectable emissions.
[c] All values in these columns are from a single sample.
[d] TVOC = sum of compounds quantified as α-pinene based on their total-ion-current areas. It does not include compounds that were not quantified by GC-MSD, including formaldehyde, acetaldehyde, and acetone.

SPECIES VARIATION AND EMISSION VARIABILITY

Terpenes are naturally occurring compounds (8) that are made up of isoprene building block units **(Fig.** 2). Monoterpenes constitute a considerable portion of the extractive content of softwood species and are responsible for much of the characteristic odor of the softwoods. The terpene content of softwoods varies with species **(Table 5)** and depends upon the locality and growing conditions. Comparison of the predominant terpene extractives in **Table 5** with the chamber data in **Table 2** and **Figure 3** indicates that emissions change in accordance with the extractives content of the species group from which the panels are manufactured. For example, in the southern pine particleboard samples, the predominant terpene emissions were α-pinene, β-pinene, and borneol, while 3-carene was not detected. The extractives of southern pine species are not known to include 3-carene (11). In contrast, particleboard samples classified as other pine emitted high concentrations of 3-carene along with the other terpenoid compounds. The other pines are generally western pine species, including ponderosa and lodgepole pine, and extractives of these woods contain substantial percentages of 3-carene (7).

The variability seen in the species groups listed in **Tables 2** and **3** is consistent with extractive variations in species. The southern pine group is made up of closely-related pines including loblolly, slash, and shortleaf pines. The terpene proportions found in these woods are similar. Consistent with these similarities, the relative standard deviations for all the emitted terpenes from southern pine paticleboards were between 44 and 78 percent. However, the other particleboard samples yielded much higher relative standard deviations (generally above 100%). The other pine group is made up of a variety of species that have considerably different extractives contents. For example, ponderosa pine contains 0.35 percent turpentine, whereas in lodgepole pine, the turpentine fraction is 0.2 percent (9). The variation in total terpene content among species probably accounts for differences in the emissions from samples within the same product-species group.

Douglas-fir contains lower levels of extractives including terpenes than pines, and hardwood extractives are generally lacking in monoterpenoid compounds. Most panels classified as primarily Douglas-fir or hardwood emitted little or no terpenes. However, one sample each of the particleboard manufactured with fir and hardwood emitted significant levels of terpenes. These samples had high terpene emissions at sampling on days 1, 2, and 4 of sample testing (24, 48, and 96 hr.), indicating that this was not a

TABLE 4.–Average 48-hour emission factors for monoterpenes, as measured by GC-MSD, for medium density fiberboard samples by manufacturer-designed predominant species group.

Detected volatile organic compound	Average 48-hour emission factors			
	Southern pine (6)[a]	Pine (5)	Hardwood (5)	Other (2)
	($\mu g \; m^{-2} h^{-1}$)			
α-pinene	ND[b]	ND	ND	ND
Camphene	ND	ND	ND	ND
β-pinene	ND	ND	ND	ND
3-carene	ND	2	ND	ND
p-cymene	0.1	0.5	0.4	ND
Limonene	ND	2	5	ND
Fenchone	NQ[c]	ND	ND	ND
Fenchol	NQ	NQ	ND	ND
Camphor	NQ	NQ	ND	ND
Borneol	2	7	2	4
Total terpenes	2.1	11.5	7.2	4
TVOC[d]	878	373	122	205
Terpenes in TVOC (%)	0.2	3	6	2

[a] Values in parentheses indicate number of samples.
[b] ND = not detected in any of the samples.
[c] NQ = detected in some samples, but not quantified.
[d] TVOC = sum of compounds quantified as α-pinene based on their total-ion-current areas. It does not include compounds that were not quantified by GC-MSD, including formaldehyde, acetaldehyde, and acetone.

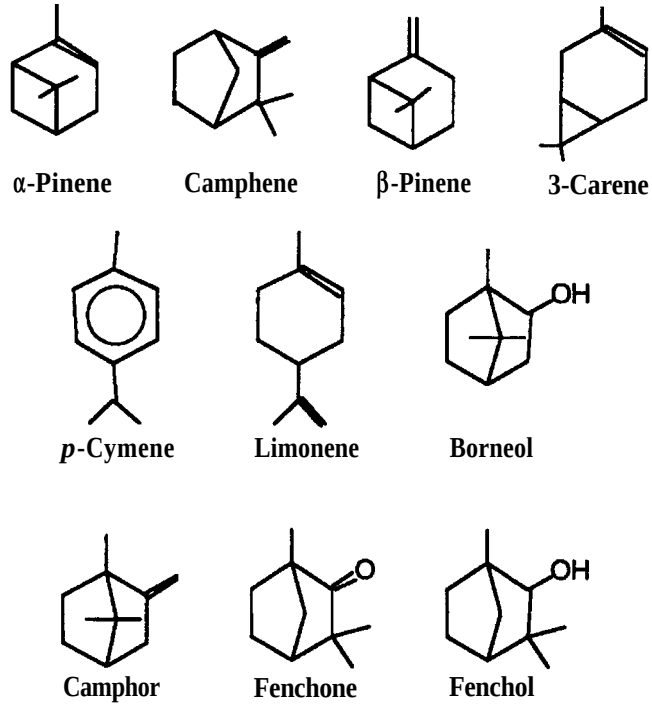

Figure 2.–Terpenes identified in emissions from particleboard and medium density fiberboard produced in the United States.

statistical or measurement error. Discussions with personnel at the Composite Panel Assoc. (Gaithersburg, Md.) indicated that this could be the result of some pine woods being used in an otherwise predominantly hardwood or Douglas-fir mill (Dan Hare, Composite Panel Assoc., 1997, personal communication).

PARTICLEBOARD COMPARED WITH MDF

In most particleboard samples, emissions of terpenes such as the pinenes, 3-carene, *p*-cymene, and borneol were readily apparent as expected. However, most of these compounds were entirely absent in tests of MDF samples **(Table 4).**

TABLE 5. – Extractive compositions of various softwood species (7, 11).

	Percentage of compound in extractives					
	α-pinene	Camphene	β-pinene	3-carene	*p*-cymene	Limonene
Loblolly pine	64	1.3	28	--	--	1.5
Slash pine	63	1.4	21	--	--	1.7
Ponderosa pine	10	1.4	16	36	1.0	12
Lodgepole pine	10	3	7	3	5	5
Douglas-fir	31	0.5	36	10	--	5

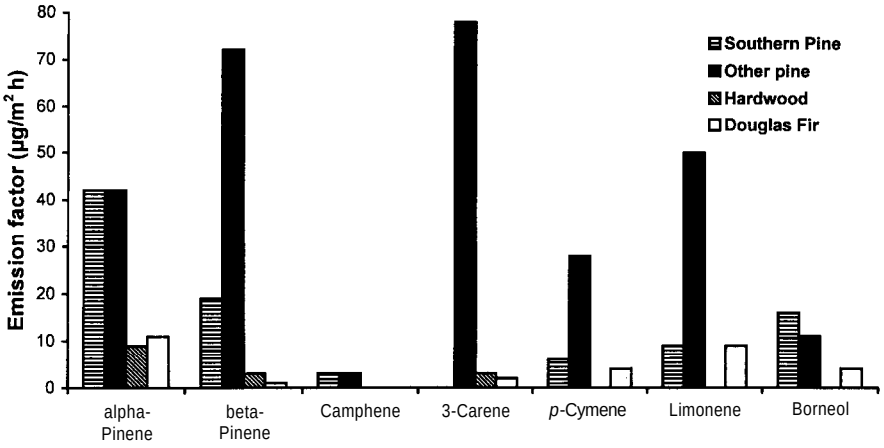

Figure 3. – Average emission factors of monoterpenes measured at 48 hours emitted from particleboard samples. Samples are grouped by manufacturer-designated predominant species used to make the product.

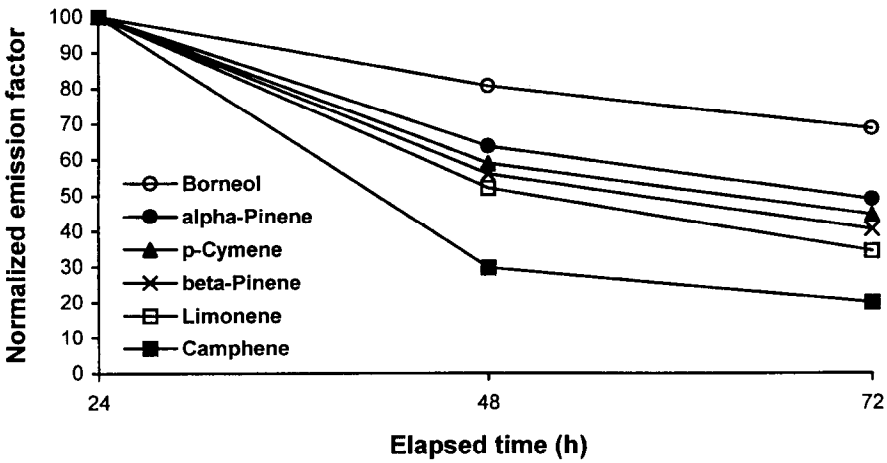

Figure 4. – Reduction of emission factors with time, normalized to 24-hour test, based on average emissions from 22 southern pine particleboard samples.

In the fiberboard industry, chips are converted to fibers using a pulping process where they are reduced by mechanical action aided by thermal softening of the lignin-rich middle lamella between wood cells. During this process, the temperature in the pressurized refiner is generally held between 160° and 185°C. This high-temperature process may drive terpenes from the furnish resulting in lower emissions by the product. Consistent with this explanation, the terpenes with the lower boiling points, such as α- and β-pinene (boiling points of 155° and 165°C respectively), were completely absent from the MDF emissions, whereas the higher boiling terpenes, such as limonene and borneol (boiling points of 176° and 212°C respectively), were present in some of the samples. In comparison, elevated temperatures and steam pressure are not used in the processing of particleboard fiber.

CONCENTRATION DECREASES WITH TIME

The chamber concentrations of terpenes emitted from both particleboard and MDF decreased during the 4 days in the chamber. Decreases ranged from 20 to 80 percent, with borneol, the highest boiling point compound, consistently showing the smallest drop. **Figure 4** shows the trends for terpenes emitted from the southern pine particleboard samples, which are representative of the general trends observed for all samples. An exponential decay has been observed for outgassing of many products, and similar results are expected for VOC emissions from particleboard and MDF panels. However, additional tests at long holding times (1 month or more) are needed to estimate the long-term emission characteristics.

The sampling and storage protocols should yield results that are representative of emissions expected immediately after use of new panels that have been stored in stacks or wrapped bundles. This is a worst-case scenario. Emissions from aged and ventilated panels are expected to be considerably lower than those reported in this study. Also, the coatings or laminates often used over composite wood products would further decrease emissions from the wood products.

NONTERPENE EMISSIONS

In addition to terpenes discussed here, several other types of compounds were emitted by particleboard and MDF pan-

TABLE 6. – Number of samples containing various nonterpene emissions from particleboard and medium density fiberboard identified in chamber tests. Tentative identification based upon MS spectral library.

Compound	Boiling point	Southern pine		Other pines		Hardwood		Douglas-fir
		Particleboard (22)[a]	MDF (6)	Particleboard (8)	MDF (5)	Particleboard (3)	MDF (5)	Particleboard (4)
	(°C)							
Aldehydes								
Formaldehyde	–21	22	6	8	4	3	5	4
Acetaldehyde	21	22	6	8	3	2	5	3
Propanal	49	12	1	4	0	2	0	0
Butanal	75	13	3	2	2	1	1	1
Pentanal	103	22	5	8	1	3	0	0
Hexanal	131	22	5	8	4	3	5	4
Heptanal	153	21	5	8	1	1	0	0
Benzaldehyde	178	22	5	8	5	2	2	1
Octanal	171	22	5	8	3	3	1	1
t-2-octenal	85 (19 mm)	22	5	8	2	3	1	2
Nonanal	191	22	5	8	4	3	1	1
Ketones								
Acetone	56	22	6	8	4	3	2	3
2-heptanone	149	22	4	8	1	1	0	0
Alcohols								
1-pentanol	136	3	2	2	0	0	0	0
1-heptanol	176	18	4	6	1	0	0	0
Other								
Acetic acid	118	3	0	1	2	2	3	0
2-pentylfuran	107	22	6	8	3	3	1	1

[a] Values in parentheses indicate number of samples.

els **(Table 6).** Of particular interest, straight-chain aldehydes were present in a large number of samples. Although aldehyde concentrations were not quantified, it is clear that aldehyde emissions, most notably hexanal, exceeded those of terpenes. While there are no reports in the literature of these small, straight-chain aldehydes being present in the extractives of wood, there are reports of aldehydes being emitted during the manufacture of wood products and from the wood products themselves (10, 18; A.O. Barry, 1995, unpublished data). Aldehyde emissions appear to result from the oxidation of some wood component, but not from additives or adhesive resins. The oxidation mechanism is not known, but could be attributable to thermal, enzymatic, or microbiological processes.

CONCLUSIONS

This study sampled particleboard and MDF products from more than 85 percent of U.S. MDF manufacturers. The VOC emissions determined in laboratory chamber tests indicated that terpene emissions from these products depend strongly on the wood species and the type of product. Particleboard emissions included many monoterpenes. The MDF emissions were much lower and included few terpenes. In general, particleboard emissions were correlated with the reported terpene content in the wood extractives of the species used to manufacture the panel. However, emissions greatly varied for similar products made from the same wood species, but manufactured by different mills. Terpene emissions decreased considerably during the 4 days they were in the test chamber. The protocol and results reported here should provide representative emission rates for new particleboard and MDF panels. This study did not address the issue of the effects of coatings or laminates, which are often used over composite wood products and which would alter the emission characteristics considerably.

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