

# VOC EMISSIONS FROM DOUGLAS-FIR LUMBER DRIED IN COMMERCIAL AND LABORATORY KILNS

Michael R. Milota  
Mark R. Lavery  
Oregon State University  
Corvallis, Oregon

Increasing human population, with its ever increasing need and desire for products, is leading to an increase in manufacturing and resource exploitation. At the same time, this population demands good air, water and scenic quality. The forest products industries are caught in the middle of this seeming contradiction. People desire quality wood products for new homes and furnishings but also demand no visible sign of the processes required to obtain the finished products. The lumber manufacturing industry crosses these invisible lines at almost every stage of production, from harvest to drying. Increased pressure to maintain and improve air and water quality is forcing the industry to monitor and control emissions from some processes.

Regulations, such as Title V of the Clean Air Act of 1990, and public attention, such as the global warming conference in Kyoto, Japan last December, are forcing the industry to address the issue of volatile organic compounds (VOC). Under Title V, fees are paid based on the quantity of emissions. Industry needs to know the amount of emissions produced to avoid paying excessive Title V fees or under reporting emissions and facing fines. Until recently (Ingram et al., 1995a; NCASI, 1996; Wu, 1997), operators had little scientific knowledge of the quantity of emissions being released from lumber dry kilns. In fact there are no published studies detailing the emission quantity from commercial kilns.

The primary objective of this study was to monitor and compare the total emissions from a commercial lumber dry kiln and a laboratory lumber dry kiln to show that the laboratory lumber dry kiln can be used to predict VOC emission levels from a commercial dry kiln.. The relationship between the speciated monoterpene emissions (quantitative and qualitative) from the two kilns was a secondary goal of this study.

## Literature Review

Kilns emit many different VOCs through their exhaust stacks in varying concentrations. These concentrations depend upon kiln schedule, the extent of fugitive gas emissions that escape the kiln via paths other than the designed exhaust (Taylor & Ingram, 1995), and the species of lumber dried, because the chemical composition varies among species.

Some emissions are likely to be condensation polymers of isoprene, predominately monoterpenes ( $C_{10}H_{16}$ ) of different configurations such as  $\alpha$ -pinene,  $\beta$ -pinene, limonene, camphene, and myrcene (Cronn et al., 1983; Ingram et al. 1995a; McDonald & Wastney, 1995). These monoterpenes have boiling points of approximately 311°F and molecular weights of approximately 136. The

monoterpenes of interest are emitted naturally from trees (Helmig & Arey, 1992) as they respire and from wood as it dries. Monoterpenes are the compounds we smell and associate with wood.

Several studies have been published focusing on emissions from lumber dried in laboratory scale kilns. Sampling the exhaust stream of a charge of southern pine dried at 180°F and 245°F, with a flame ionization detector (FID), Ingram et al. (1995b) reported emissions of 2.75 g/kg<sub>ODwood</sub>. Chemical analysis of condensed volatiles from radiata pine dried 248°F and 284°F revealed 0.23 and 0.32 g/kg<sub>ODwood</sub> respectively (McDonald & Wastney, 1995). Drying charges of 1,000 board feet and sampling the exhaust stream with an FID the NCASI (1996) reported; 0.09 g/kg<sub>ODwood</sub> for redwood, 0.08 g/kg<sub>ODwood</sub> for cedar, 0.14 g/kg<sub>ODwood</sub> for Douglas-fir sapwood, 0.15 g/kg<sub>ODwood</sub> for hemlock, 0.22 g/kg<sub>ODwood</sub> for Coastal Douglas-fir, 0.32 and 0.39 g/kg<sub>ODwood</sub> for white and grand fir, and 0.43 g/kg<sub>ODwood</sub> for Douglas-fir heartwood, 0.99 g/kg<sub>ODwood</sub> for sugar pine, 1.0 g/kg<sub>ODwood</sub> for ponderosa pine, 1.29 g/kg<sub>ODwood</sub> for western white pine, and 1.02 g/kg<sub>ODwood</sub> and 1.53 g/kg<sub>ODwood</sub> for loblolly pine from Arkansas and Texas, respectively. This NCASI study indicates that southern pines tend to release more volatiles during drying, however drying temperatures tend to be higher. Using EPA Method 25D, Dallons et al. (1994) determined that approximately 1.1 g/kg<sub>ODwood</sub> of emissions were released from southern pine as it is dried. The limited literature suggests that a FID may indicate higher emission rates than those determined by condensing. This may be due to more complete detection with the FID. A value of 1 g/kg<sub>ODwood</sub> is equivalent to approximately 2 lbs/mbf for Douglas-fir dimension lumber.

At this meeting last year we reported work by Milota and Wu (1997). Since that time we have added a correction to the calculation method for total hydrocarbon. Part of this correction was due to the suppression of the detector reading due to moisture in the exhaust gas which was not accounted for in the original work. The revision of the work increases the original emissions estimate for coastal Douglas-fir to 0.8 g/kg<sub>ODwood</sub>. This is approximately 1.6 pounds per 1000 board feet. Based on this work, it is likely that a 25°F increase in the dry-bulb temperature or a 12% increase in the initial moisture content will likely result in a 0.1 lb/mbf increase in the emissions in the range of 160 to 200°F. A revised publication of this work has been submitted to the Forest Product Journal.

## Materials and Methods

### Commercial Charges

Three charges of freshly sawn, Douglas-fir (*Pseudotsuga menziesii*), nominal 2- by 6-inch lumber were dried in a commercial kiln. The wood was sawn, sorted by length, and solid-piled during the evening prior to testing. For charges one and two, boards were removed from the solid-piled packages to create charges for the laboratory kiln tests, detailed below. This was done to have matched lumber dried in both the laboratory kiln and commercial kiln. The wood was then stacked on 0.75-inch stickers. After stacking, one-third of the packages from charge one and two were weighed.

The packages of lumber were stacked on the kiln carts three packages high (approximately 15 feet) and two packages wide (approximately eight feet). The

weighed packages were placed in the middle course of packages. The overall length of the kiln charge was 64 feet.

After completion of schedule, the charge was pushed into the covered cooling area where it was broken down the next morning. The packages that were weighed green were again weighed to get their kiln dry weights. The boards from all three charges were processed over a Wagner 683 in-line moisture meter to determine the moisture content at the end of the schedule. Hand-held meter readings with a pin-type meter were also taken to verify the readings from the in-line meter.

### **Laboratory Charges**

The lumber to be dried in the laboratory kiln was selected such that the relative volume of each length was the same in both the laboratory and commercial kilns. This was done because 20-foot lengths of 2- by 6-inch lumber potentially have different wood characteristics than do 12-foot lengths of 2- by 6-inch lumber. The longer boards may have come from a larger diameter tree and/or from the center of the log, and therefore contain a larger percentage of heartwood, than the shorter length boards. To do this twelve 20-foot, eight 14-foot, and eight 12-foot pieces were sampled. An attempt was made to select pieces with wood properties, such as percent heartwood and number of knots, that were representative of the commercial charge. This selection was done visually and not quantitatively.

The 20-, 14-, and 12-foot lumber was cut into 48-inch pre-samples with a radial arm saw. The 48-inch pre-sample boards were organized into four piles so that the ends and middle pieces from the long boards were equally represented in each charge. The 48-inch pre-samples were wrapped in plastic and the seams were sealed with duct tape, four bundles per lab kiln charge. Each bundle was labeled with date and lab charge identification number and stored at -10°F until the laboratory kiln charges were run.

### **Commercial Kiln**

The commercial kiln was a 64-foot single track with a heat exchanger located on a catwalk above the loading doors. A sampling probe, pitot tube, and thermocouple were inserted in to the kiln exhaust line prior to the heat exchanger. A total hydrocarbon analyzer (THA) drew a 3 l/min sample through a heated sampling line from the sample probe. The probe was a 0.5-inch diameter stainless steel tube with three 0.0625-inch diameter holes drilled on one side of the tube, at the center and 16.7% of the diameter of the stack (12-inches) from each end. They faced into the flow of the exhaust. A 0.8 l/m sample was also drawn from the probe, through an ice chilled condenser, a water trap, two activated charcoal tubes, a flow meter, and a small pump. The condensate and organic adsorbed onto the charcoal were chemically analyzed using a gas chromatograph and mass spectrophotometer (GC/MS).

## Temperature and Relative Humidity Sensors

A relative humidity sensor and thermocouple were placed under the eave of the control building, exposed to ambient air. A sling psychrometer was also used twice daily to verify the humidity readings. Five thermocouples were located inside the kiln, two on each side of the load and one on the wet-bulb sensor. Thermocouples were also placed in the sampling section and before and after the heat exchanger.

## Variable Frequency Drive

A 0-5 v remote output signal proportional to the blower rpm was read and recorded from the variable frequency drive (VFD) controlling the blower motor in the heat exchanger. Prior to conducting the study, a pitot tube was used to measure flow through the sample section throughout the range of blower rpm with the fans running in both directions. This data was used to develop a relationship between the 0-5 v signal and the flow through the heat exchanger. This relationship was used to determine the venting rate during the test charges.

## Sampling

Condensate samples from the heat exchanger drain line were collected every four hours during the schedule. The flow rate of condensate was measured by timing how long it took to collect 500 ml in a graduated cylinder. The condensate samples were combined, sealed, and stored in an ice-chilled cooler until organic extraction could be performed.

The condensate collected in the water trap of the monoterpene sampling train was measured every four hours, and combined in a 2000-ml flask. Condensate from the water trap was stored in the same manner as the condensate from the heat exchanger.

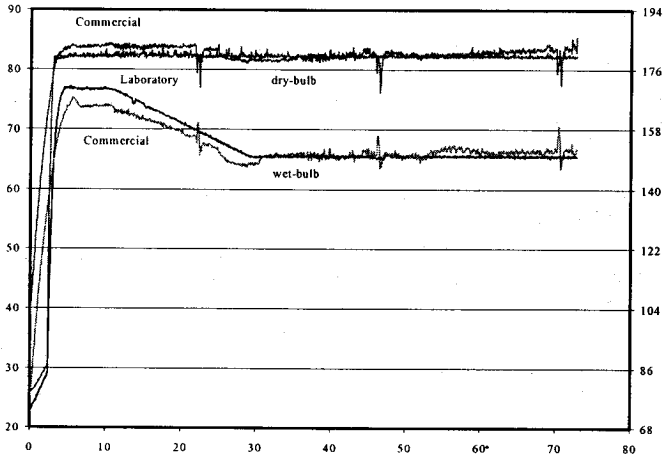
The charcoal tubes were changed every few hours depended upon the concentration of reading of the THA. In the beginning of the schedule when the hydrocarbon concentration was relatively high, the activated charcoal tubes were changed often, every 30-45 minutes. As the hydrocarbon concentration in the exhaust decreased during the schedule, the sampling interval increased to as long as six hours. The ends of each tube were sealed as it was removed from the sampling line. These were placed in plastic bags and stored in an ice-chest until organic extraction could be performed.

The zero and span on the THA were calibrated every few hours. Grade 5.0 Hydrogen was used for the ionization flame. Grade 5.0 Nitrogen was used for the zero gas and purge gas. Propane at 885 ppmv in air used for the span calibration. The maximum adjustment required was less than three percent of the reading.

## Laboratory Kiln

The laboratory kiln had compressed house air metered into it by an MKS Instruments, Inc. 0-50 liter/minute Type 0558A mass flow meter and Type 1559A mass flow controller. The rate of airflow was controlled based on the wet-bulb temperature much the same as vent would be controlled on a commercial kiln. A minimum of 4.0 liters/minute, slightly more than that being drawn by the THA and the adsorption sampling train (0.8 liter/minute), was maintained. This gave a slightly higher than ambient pressure in the kiln ensuring that any leakage was out of the kiln.

Twenty-four hours before each laboratory kiln charge the wood was removed from the freezer and allowed to thaw for approximately 20 hours. Packages remained sealed in plastic to help retain any organic compounds. Just prior to loading the kiln, the 48-inch pre-samples were trimmed to 44-inches by trimming two inches from each end and each board was weighed. This was done to obtain "fresh" ends, free from any end drying effects that may have occurred during storage. Eight laboratory kiln charges were run, four from each of the first two commercial kiln charges. Each was two boards wide and ten courses high on 0.75 inch stickers. The schedules in the lab and mill were as similar as possible (FIGURE 1). The same procedure for sample collection and storage as detailed for the commercial kiln were followed for the condensate in the adsorption sampling train and the activated charcoal tubes. Also, the THA was operated in a similar manner.



**FIGURE 1.** Matched drying schedules, laboratory and commercial, Douglas-fir. The laboratory kiln showed slightly better control with less variation in temperature. The commercial kiln had fan reversals so spikes in temperatures are present.

All sample boards were weighed after kiln drying then oven dried and reweighed. Each oven dried board had its thickness and width measured in two places and the percentage of heartwood measured at each end of the board. Additionally the numbers of growth rings per inch were counted.

### **Chemical Analysis**

A standard dichloromethane solvent solution containing one gram/liter undecane,  $C_{11}H_{24}$  as an internal standard was used to extract the condensate and activated charcoal samples.

Condensate samples were extracted twice with five ml of standard dichloromethane solvent solution. The two five-ml solvent samples were combined in a small Erlenmeyer flask. The remaining water in the separatory funnel was discarded. An estimated 95% of the organics were extracted. Granules of anhydrous sodium sulfate ( $Na_2SO_4 - 7H_2O$ ) were used to dry the solvent sample (Adams, 1991). The sample was stored in a crimp-seal vial at 40°F in a dark environment. Chromatographic analysis was performed within two weeks collection.

The activated charcoal was removed from the glass tubes and transferred into two-ml vials. Each series pair of charcoal tubes was combined into one vial for analysis. One ml of the standard dichloromethane solvent solution was pipetted into each vial. The vials were sealed with screw caps and sonicated for 15 minutes. The liquid fraction was then removed from the vials and filtered to ensure the samples were free of particulate. Typically, less than one ml of solvent/sample was collected because some solvent remained wetting the charcoal. This extraction process was repeated and the extractants were combined in an auto-sampler crimp seal vial. These were sealed and stored as described above.

### **GC-MS Analysis**

A Hewlett Packard 5890 Series II gas chromatograph was used to separate the monoterpenes. Identification of the individual components of the samples were determined by retention time and comparison of mass spectra with the LIST/EPA/MSDC 54K Mass Spectral Library and Hewlett Packard MS Chemstation (Catalog #HP G1030A). Details can be found in Lavery (1998).

The dry gas flow rate, moisture content of the wood, hydrocarbon emissions, and monoterpene emissions from the kiln were calculated. Summing the emissions from each time three-minute interval,  $j$ , from the beginning of the drying schedule to any target lumber moisture content or time yields total emissions to that time or moisture content. In order to calculate the water loss rate from the wood, absolute humidity in and out of the kiln were used in conjunction with the dry gas flow rate. Integration of the calculated water loss rate from the beginning to the drying schedule to its completion should be equivalent to the water loss from the wood.

## Humidity

Vapor pressure was calculated for the wet-bulb in the kiln and the absolute humidity inside the kiln was calculated as:

$$y = \frac{MW_{\text{water}}}{MW_{\text{air}}} \frac{1}{\frac{p}{p_w^o} - 1} - \left( (T_{DB} - T_{WB}) \left( \frac{h_g/k_y}{\lambda} \right) \right) \quad (1)$$

where  $p = 101,325 \text{ Pa}$ ,  $h_g/k_y = 0.95 \text{ kJ}/(\text{kg}\cdot\text{K})$ , and  $\lambda = 2419.3 \text{ kJ}/\text{kg}$ . The molal humidity inside the kiln was calculated as:

$$Y' = \frac{MW_{\text{air}}}{MW_{\text{water}}} * y \quad (2)$$

## Dry Gas Flow Rate

The total volumetric gas flow rate leaving the commercial kiln was converted into total molal flow rate using the ideal gas law. This was then divided by the molal humidity to obtain the molal dry gas flow rate,  $G'$ . Multiplying  $G'$  by the molecular weight of air gives the dry gas mass flow rate,  $G$ .

The volumetric gas flow rate entering the laboratory kiln was converted to a dry gas molal flow rate,  $G'$ , using the ideal gas law. The humidity in the inlet air was negligible such that no humidity adjustment was necessary. Multiplying  $G'$  by the molecular weight of air gives the dry gas mass flow rate,  $G$ .

## Water Balance

The moisture content,  $X_n$ , of the wood at interval  $n$  in the schedule was determined by:

$$X_n = X_o - 100 * \frac{\sum_{j=1}^{j=n} G_j * y_j * \Delta t_j}{m_{OD}} \quad (3)$$

At the end of drying, the calculated moisture content was compared to the actual moisture content as determined by the oven dry method to obtain a moisture balance.

## Total Hydrocarbon Analysis

The reading from the THA was adjusted for humidity in the gas stream, using

$$THA_{moiscor} = \frac{THA}{0.21 * \exp(-6.649y) + 0.79} \quad (4)$$

This relationship was determined in a separate experiment in which known concentrations of moisture and hydrocarbon were measured by the detector. Moisture in the sample stream tends to depress the detector response. The THA reading was then converted from a total gas value to a value based on the dry gas:

$$THA_{dry} = THA_{moiscor} * (1 + Y') \quad (5)$$

The hydrocarbon emission rate (g/min) was calculated as:

$$G_H = (G') \left( \frac{THA_{dry}}{1,000,000} \right) (MW_{propane}) \left( 1,000 \frac{g}{1 kg} \right) \quad (6)$$

Finally, the total mass of emissions at 12% moisture content was determined by:

$$m_H = \sum_{j=1}^n G_{H_j} * \Delta t_j \quad (7)$$

where n corresponds to the interval at which the wood moisture content is 12% as determined by equation 3.

## Monoterpene Quantity

The raw concentrations determined by the GC-MS were scaled to adjust for run specific detector conditions, by scaling each concentration by the concentrations obtained for undecane. Thus:

(8)



where  $i$  represents the  $i^{\text{th}}$  monoterpene detected. The mass of each monoterpene,  $m_i$ , in the sample was calculated by multiplying the solvent volume used to extract the sample times the concentration.

$$m_i = X'_i * V_s \quad (9)$$

The total mass of each monoterpene emitted from the kiln,  $M_i$ , was obtained using the ratio of the dry gas flow rates from the kiln and the sampling line. Thus

$$M_i = \sum_{j=1}^n \left( \frac{G'_j}{G'_{\text{CH}_j}} \right) * (m_i)_j \quad (10)$$

$j$  is a time interval and  $n$  is the time interval corresponding to 12% moisture content.

## Results and Discussion

### Wood Properties

Analysis of the packages of lumber used in the laboratory kiln revealed (TABLE 1) that the initial moisture content was about 61% as compared to 59% for the commercial packages. This discrepancy is likely due to the laboratory calculation being based upon the oven-dry method, whereas the calculations for the commercial charges are based upon kiln dry moisture meter readings and package weights. Longer boards yielded samples with greater amounts of heartwood and lower moisture contents. This is likely due to longer boards originating from closer to the center of the log. The number of rings per inch is roughly 5.9 for all lengths of original board. The specific gravity for all lengths was approximately 0.48 in the oven-dry condition.

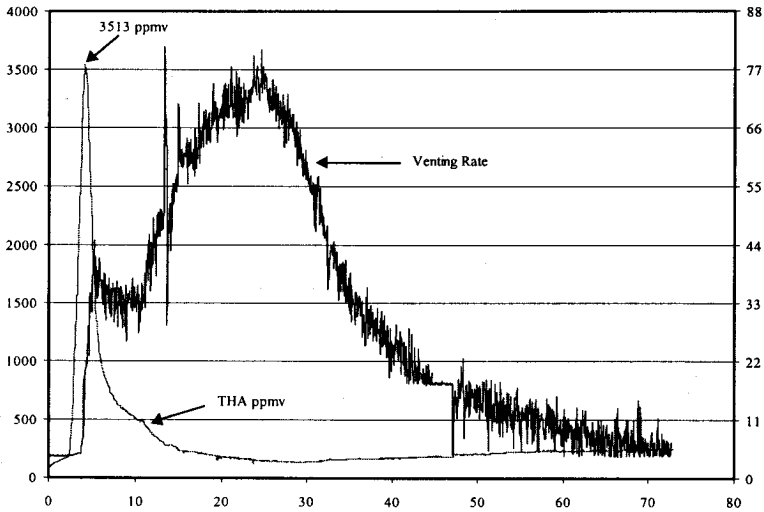
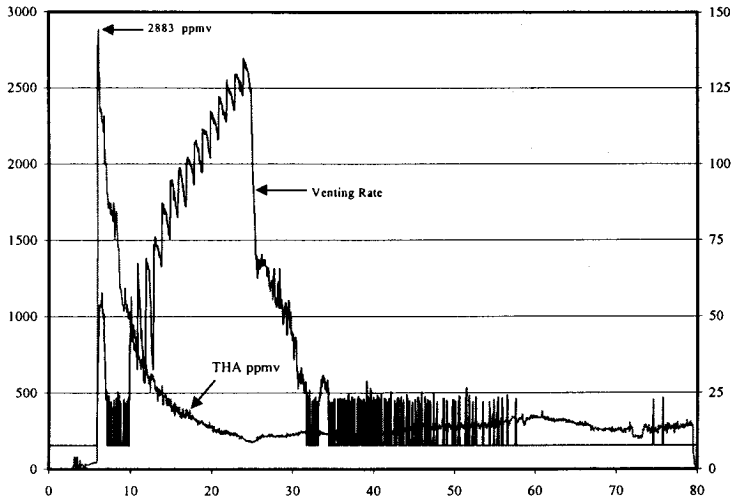
The initial moisture content of the charges did not play a major role in the total cumulative emissions, however, initial moisture contents did not vary over a wide range. The total emissions for all charges of 2x6 Douglas-fir, as measured by a THA, were in the range of 1.0 g/kg<sub>ODwood</sub>. Analysis of these lumber charges by adsorption of volatiles with activated charcoal revealed total monoterpene emissions of approximately 0.2 g/kg<sub>ODwood</sub>.

## Hydrocarbon Concentration

The hydrocarbon concentration in the exhaust air of both the laboratory and commercial kilns increased rapidly from near zero to approximately 3000 ppmv (dry basis) at approximately six hours into the schedule when venting began (FIGURE 2). The concentration in the commercial kiln probably increased over the six-hour period; however, until kiln air was drawn through the sampling section, the hydrocarbon concentration in the kiln was not actually recorded by the THA. After venting began at the six-hour point in the schedule, the hydrocarbon concentration rapidly decreased. In both the commercial and the laboratory kilns, the hydrocarbon concentration later in the drying schedule is 200 to 450 ppmv.

**TABLE 1.** Physical parameters of the 2x6 Douglas-fir lumber. Cumulative emissions are adjusted to the point when the charged achieved a 12 % moisture content. Heartwood %, ring/inch, and specific gravity for the commercial charges are the average of the measurements taken of the laboratory samples. Blank spaces represent no data collected.

Charge ID	Green MC %	Heart %	Rings #/inch	Specific Gravity	g Monoterpene kg <sub>ODWOOD</sub>	g THC kg <sub>ODWOOD</sub>	
					@12% MC	@ 12% MC	
Commercial 1	55.98	77	7.1	0.51	0.42		
LABORATORY	1	63.11	84	5.8	0.50	0.30	1.22
	2	63.62	74	6.7	0.50	0.12	1.18
	3	60.11	74	7.6	0.50		0.81
	4	50.05	76	8.3	0.52		0.89
Commercial 2	62.33	78	5.4	0.50	0.21	1.16	
LABORATORY	5	64.15	79	5.9	0.47	0.22	1.03
	6	64.47	77	4.8	0.46		0.92
	7	64.66	82	5.5	0.45	0.21	0.91
	8	63.93	74	5.5	0.47		0.75
Commercial 3	59.00	78	6.3	0.46		0.97	
Board Length							
12-	Foot	78.92	64	5.3	0.47		
14-		67.62	78	7.0	0.48		
20-		54.17	82	6.3	0.49		



**FIGURE 2.** Hydrocarbon concentration and vent rate for the commercial (A) and laboratory (B) kilns.

## Rate of Emissions Release

Initially the release of emissions is very low because there is little or no venting until the wet-bulb temperature reaches set-point (FIGURE 3). Then, the rate of emissions increases rapidly when the kilns begin to vent. This is indicated by the steep portion of the THA lines in FIGURE 3. The rate of emissions release remained relatively high from hour 6 to hour 30 in the schedule. This is demonstrated by the moderately-sloped linear part of the cumulative emissions curve in FIGURE 3.

After hour 30, the emissions rate decreased, rapidly as indicated by the knee in the cumulative emissions curve in FIGURE 3. For the remainder of the drying schedule the emissions rate decreased slowly.

The total quantity of hydrocarbons released averaged 1.07 g/kg<sub>ODwood</sub> (2.05 lbs/mbf nominal) for commercial kiln charges two and three. A THC value was not attained for charge one because of a problem with the detector. The total emissions values for each of the two commercial kiln charges are within 21% of each other. It is not known if the difference is due to actual variability of the VOCs released or sampling error. The measured unit emissions are 2.5 times the value reported for Douglas-fir heartwood by NCASI (0.43 g/kg<sub>ODwood</sub>). In our earlier work with coastal Douglas-fir, we obtained 0.8 g/kg<sub>ODwood</sub>. However, it should be noted that NCASI measure only 1.02 to 1.53 g/kg<sub>ODwood</sub> for southern pine while Ingram et al. Measured 2.75 g/kg<sub>ODwood</sub>.

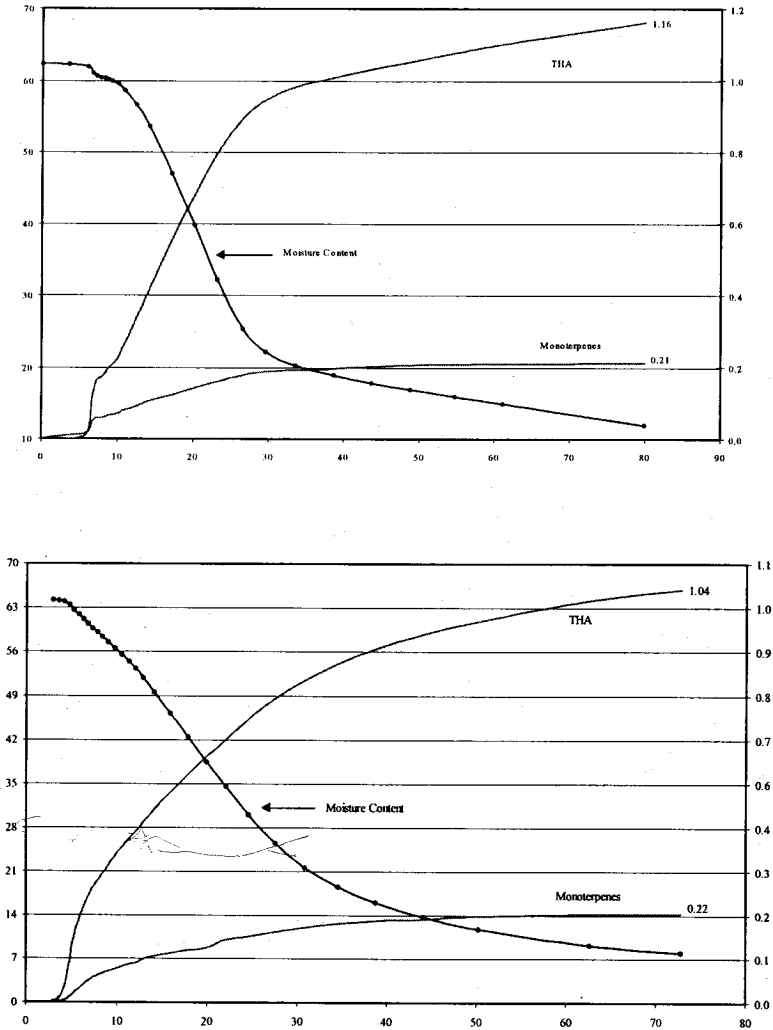
Between hours 12 and 24, as the moisture content of the wood decreased rapidly, the cumulative emissions increased rapidly (FIGURE 3). Later in drying, from 36 hours to the end of the schedule, both the drying rate and the emissions rate were much lower. This suggests that emissions may be related to moisture content. When cumulative emissions are plotted as a function of moisture content (FIGURE 4) it is clear that the quantity of emissions released was nearly proportional to the change in moisture content from a charge moisture content of approximately 56% to the end of the schedule. Many of the volatile compounds released from Douglas-fir as it dries are not soluble in water, however, it is possible that they may move to the drying surface in conjunction with the migration of water. This observation is significant in that drying to different final moisture contents will give different total emissions; however, the emission level at any final moisture content should be easy to predict.

## Monoterpenes

Speciated information for both the commercial and laboratory kilns is shown in FIGURE 5.  $\alpha$ -pinene was the dominantly emitted monoterpene.  $\alpha$ -pinene is expected to be the most abundant species because it is present in relatively high concentrations in conifers. These same compounds, in similar quantities were measured from the laboratory kiln. Initially there was a high rate of monoterpene emissions but as the schedule continued the rate decreased. This trend mirrors the trend seen for total hydrocarbons as measured by the THA. The relative ratio of detected monoterpenes is similar between commercial kiln runs one and two but the total quantity measured is not. The total detected for run one was 0.41 g/kg<sub>ODwood</sub>, where as in run two only 0.22 g/kg<sub>ODwood</sub> was collected. Wood

properties do not seem to explain the difference in total monoterpenes collected because **TABLE 1** indicates that the properties were similar.

Speciated gaseous emissions collected from veneer dryers (Cronn et al., 1983) include the monoterpenes detected in the exhaust from the lumber dry kiln. The relative quantities of monoterpenes detected in the veneer drier exhaust is similar to that observed for the lumber dry kiln, with  $\alpha$ -pinene being detected in concentrations several times greater than the others.



**FIGURE 3.** Cumulative emissions total hydrocarbon and monoterpene emissions for the commercial (A) and laboratory (B) kilns.

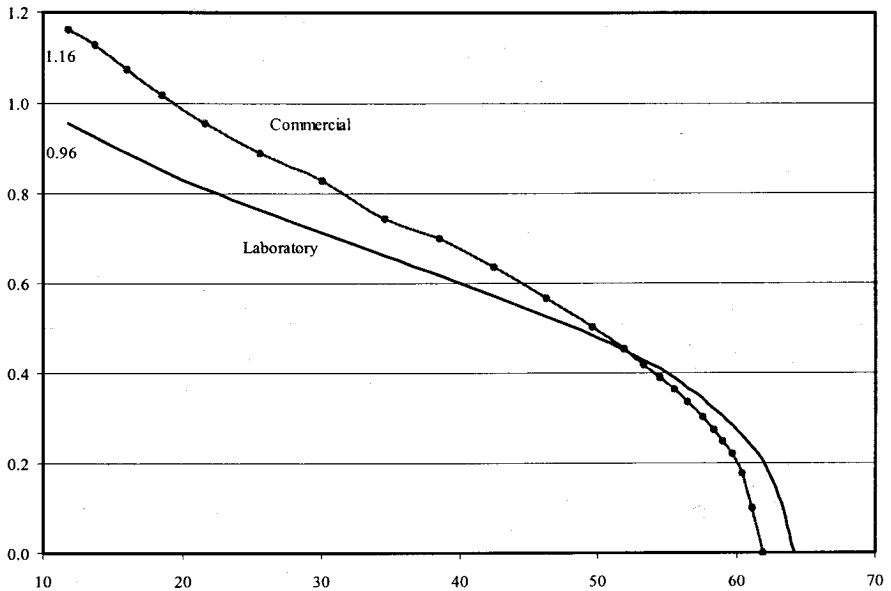


FIGURE 4. Cumulative emissions versus moisture content for a commercial compared to a lab charge.

### Heat Exchanger Condensate

There were only two monoterpenes identified in the condensate from the heat exchanger,  $\alpha$ -terpineol (0.029 mg/kgOD<sub>wood</sub>) and  $\alpha$ -terpineol (0.014 mg/kgOD<sub>wood</sub>) (FIGURE 5). A total of 1,193 liters of water was calculated to be condensed in the heat exchanger and approximately 0.043 mg/kgOD<sub>wood</sub> of monoterpenes.  $\alpha$ -terpineol is slightly soluble in water. The only other monoterpene, of those detected in the exhaust stream, which is also soluble in water is  $\alpha$ -pinene. However, the boiling point of  $\alpha$ -pinene is 311°F as compared to 422°F for  $\alpha$ -terpineol. The temperature of the condensate leaving the heat exchanger was approximately 110°F. It is likely that this temperature was high enough to volatilize a significantly larger portion of the  $\alpha$ -pinene such that it was undetected.

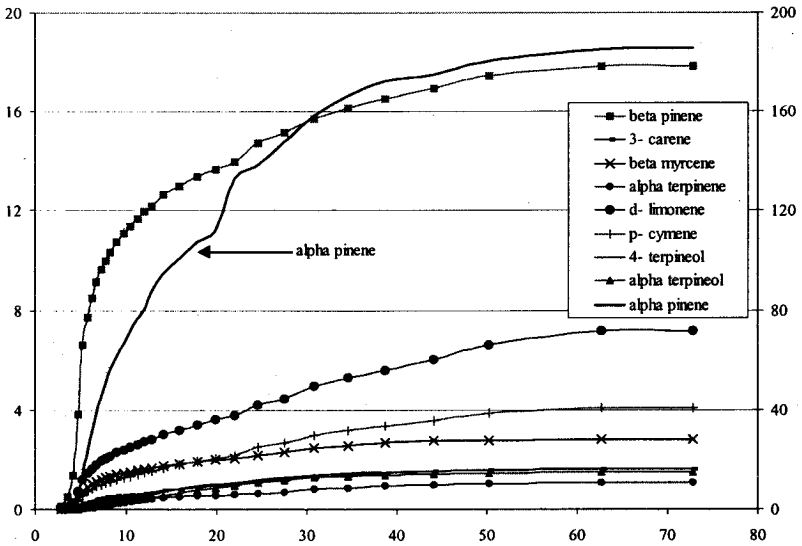
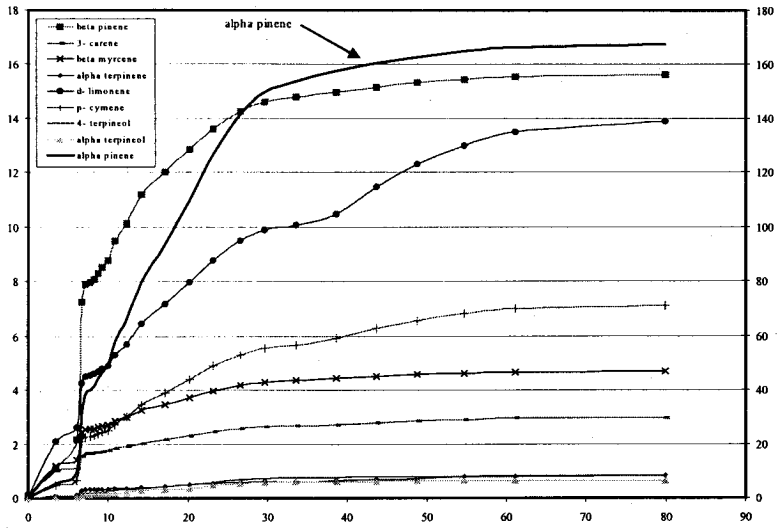


FIGURE 5. Cumulative monoterpene emissions from the commercial (A) and laboratory (B) kilns.

## Conclusions

The laboratory kiln performs like a scaled down version of the commercial lumber dry kiln in many respects. The venting rate versus time in each kiln follows a similar pattern. In addition, the peak hydrocarbon concentrations were similar and occurred in each kiln type approximately six hours into the schedule. Further, in each kiln the hydrocarbon concentrations reach a minimum 25 to 30 hours into the schedule, then increase slightly as less air is vented later in the schedule. In each kiln the emissions later in the schedule ranged from 250 to 400 ppmv.

The time during the schedule when hydrocarbons are released is similar for both kilns with half of the total hydrocarbon emissions being released during the first 15 to 18 hours. When emissions are plotted against moisture content the same profile is seen for the laboratory and commercial kilns.

Similar total amounts of hydrocarbon emissions were released, and average of 0.96 g/kgODwood from the laboratory kiln and 1.07 g/kgODwood from the commercial kiln. In environmental field sampling agreement of between 10 and 20% is considered good. In addition, the GC-MS analysis indicated that the monoterpene emissions from each kiln were emitted in similar ratios.

The evidence; similar concentrations vs. time, venting profiles vs. time, emission profiles vs. time, emission profiles vs. moisture content, total hydrocarbon emissions, and monoterpene species ratios all indicate that the laboratory kiln is an effective tool in predicting emissions from larger kilns. The laboratory kiln offers lower wood use, no fugitive emissions, better schedule control, and better control over the monitoring. The disadvantage of the laboratory technique is the necessity to obtain a small representative wood sample of an entire commercial kiln charge of lumber or the production from a mill.

Total hydrocarbon emissions were approximately 1.0 g VOC / kg oven dry 2x6 Douglas-fir. This is approximately 2 pounds per mbf.

## Nomenclature

D	thickness of oven dry samples, meters
G'	dry gas flow rate, kgmols/minute
G	dry gas flow rate, kg/minute
G <sub>CH</sub>	dry gas flow rate in the adsorption sampling train, kgmol/minute
G <sub>H</sub>	hydrocarbon emission rate, g/min
h <sub>g</sub> /k <sub>y</sub>	psychrometric ratio, kJ/(kg-K)
L	length of oven dry samples, meters
m <sub>i</sub>	quantity of monoterpene in a given sample, mg
M <sub>i</sub>	quantity of monoterpene collected, for a given time interval, mg
m <sub>OD</sub>	oven dry weight of wood, kg
MW	molecular weight kg/kgmol
p	total pressure, Pa
p <sub>v</sub>	vapor pressure, Pa
SG	specific gravity
T	temperature, C



$THA_{moiscor}$	THA reading adjusted for humidity, ppmv as propane
$THA_{dry}$	THA reading on a dry gas basis, ppmv as propane
t	time, min
$V_s$	quantity of solvent used to extract samples, ml
W	width of oven dry samples, meters
$x_j$	raw values returned by GC-MS, mg/liter
$x_u$	undecane concentration returned by the GC-MS, mg/liter
$x'_i$	raw values adjusted for detector response, mg/liter
X <sub>O</sub>	initial moisture content
X	moisture content, %
y	absolute humidity, kg <sub>water</sub> /kg <sub>air</sub>
Y'	molal humidity, kg <sub>mol</sub> <sub>water</sub> /kg <sub>mol</sub> <sub>air</sub>
$\rho_{H_2O}$	density of water
$\lambda$	latent heat, kJ/kg
$\psi_C$	relative humidity, %

### Subscripts

air	air
db	drybulb
j	time index
o	initial
OD	ovendry
propane	propane
water	water
wb	wet bulb

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