CHANGES IN THE VOC EMISSIONS FROM DOUGLAS-FIR LUMBER WITH TEMPERATURE AND HUMIDITY

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Until the early to mid part of this century, the capacity of nature was considered satisfactory to reduce air and water pollutants to safe levels because manufacturing was carried out in relatively small facilities that were separated geographically. Population increases, urbanization, and industrialization resulted in some attempts to regulate the emission of smoke in the 1930's, but these problems were largely ignored until after the war effort in the 1940's. The Air Pollution Control Act of 1955 was the first strong national effort to address air pollution. It was followed by additional Clean Air Acts in 1963, 1967, and 1970 (Vincoli, 1993).

The 1970 Act was, by far, the most extensive of the three, authorizing the then new EPA to establish National Ambient Air Quality Standards (NAAQS). The EPA has applied NAAQS to seven pollutants: particulate smaller than 10 microns[2] (PM_{10}), sulphur oxides, nitrogen dioxide, lead, carbon monoxide, hydrocarbons, and ozone (EPA, 1993). States were required to develop implementation plans (SIPs) by region. Through amendments in 1977, the act was strengthened and the concept of preventing significant deterioration (PSD) originated.

These 40 years of legislation laid the groundwork for the Clean Air Act Amendments of 1990, often referred to as simply the Clean Air Act (CAA), which is extremely complex and may take as long as 20 years to fully phase in. There are seven titles under the 1990 CAA: I. SIPs, NAAQS, PSDs, and nonattainment; II Emissions from moving sources; III Air toxics; IV Acid deposition control; V. Permits; VI. Stratospheric ozone protection; and VII. Enforcement (EPA, 1993). The work in this paper is oriented toward assisting industry with Title V compliance.

Title V requires permits for significant sources of hydrocarbon emissions, that is, those greater than 10 to 100 tons per year depending on the regional ambient air quality. These permits, combined with the SIP are the main ways in which the EPA enforces attainment of the NAAQS. Each permit must contain emission limits, record keeping and reporting procedures, a schedule for compliance, and a way for the state to ensure compliance. The fees associated with the permits are based on the quantity of emissions. Hence it is important for companies to know the

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[2] This may change to 2.5 microns by the time of publication.

hydrocarbon emissions coming from lumber dry kilns as well as other equipment on site (Klaber and Weiss, 1994).

The main objective of this work is to determine if the quantity of hydrocarbon emissions from Douglas-fir lumber changes as temperature and humidity in the dryer change. If the drying schedule affects emissions, then manufacturers may be able to minimize emissions by altering the operating conditions. A secondary objective was to identify when during the drying schedule emissions occur. The design of control equipment, if necessary, would require both the effluent volume and concentration which both vary during the batch drying process.

Literature Review

Compounds emitted from softwood lumber during drying will most likely be derivatives of isoprene such as α-pinene, β-pinene, camphene, limonene, and myrcene (Ingram et al.1995a; McDonald and Wastney, 1995; Chronn et al. 1983). These all have normal boiling points above 155°C and molecular weights of approximately 136. These are among the many compounds also emitted from the forest (Helmig and Arey, 1992; Guenther et al. 1994). Some organic acids, such as acetic, are also likely to be emitted from the breakdown of wood hemicelluloses.

Emissions from commercial lumber dry kilns are not easy to measure because venting occurs at multiple locations and fugitive emissions often occur around doors. The modulated control and lack of a duct in which a velocity profile can be developed make it difficult to measure the airflow. We have found no data in the open literature reporting emissions from commercial kilns. On a laboratory scale several investigators have measured drying emissions from lumber. Ingram et al. (1995b) reported approximately 2.75 g/kg_{ODwood} at temperatures of 245°F (118.3°C) and 180°F (82.2°C) as measured with a flame ionization detector (FID) on southern pine. Knots contributed significantly to the emissions. In contrast, McDonald and Wastney (1995) reported 0.23 and 0.32 g/kg_{ODwood} at 248°F (120°C) and 284°F (140°C), respectively, by doing a chemical analysis on condensate and dry-ice-trapped volatiles obtained from drying radiata pine. Perhaps the largest set of laboratory data is reported by NCASI (1996). They report 0.09 g/kg_{ODwood} for redwood, 0.08 g/kg_{ODwood} for cedar, 0.14 g/kg_{ODwood} for Douglas-fir sapwood, 0.15 g/kg_{ODwood} for hemlock, 0.22 g/kg_{ODwood} for Coastal Douglas-fir, 0.32 and 0.39 g/kg_{ODwood} for white and grand fir, and 0.43 g/kg_{ODwood} for Douglas-fir heartwood. They also report 1.0 g/kg_{ODwood} for ponderosa pine, 0.99 for sugar pine, 1.29 g/kg_{ODwood} for western white pine, and 1.02 and 1.53 g/kg_{ODwood} for loblolly pine from Arkansas and Texas as measured with an FID. All data was taken on charges of approximately 1000 board feet. Clearly, the pines have greater emissions than the other softwood species tested. Also, it appears that measurements made with an FID result in greater values than the analysis of condensate. This suggests that not all the organics are condensed, even in dry ice-acetone traps.

Attempts have been made to relate the THC emissions to a chemical analysis of the wood. Ingram et al. (1995a) report less than half of the monoterpenes detected by a chemical analysis on the wood are detected at the dryer exhaust. NCASI (1996) reports VOC emissions ranging from equal to, to three times greater than the turpentine loss from the wood as detected by chemical analysis before and after drying. Dallons et al. (1994) used a similar approach, EPA Method 25D, and

obtained emission an factor of approximately 1.1 g/kg$_{ODwood}$ for southern pine, considerably less than the values obtained by Ingram et al. (1995). However, the samples of Dallons did not include knots.

Procedure

A small laboratory kiln was configured so that the total hydrocarbon content and flowrate of the gas leaving the kiln could be measured. Based on these values, the mass of emissions was calculated for several drying schedules. Wu (1997) contains the detailed procedure and experimental results.

Equipment

The overall equipment layout is shown in Figure 1. The dry-bulb temperature is controlled by the steam flow through a pneumatic valve (K2) to heating coils (K1). Condensate is returned to the boiler (K3). The steam spray is disabled so no water is added to the kiln atmosphere except for evaporation from the wood and wet-bulb sensor and from water vapor entering with make-up air. The kiln's vents are sealed and exhaust air is pumped from the kiln through an all-glass venting system. Due to the action of the pump, the gas pressure in the kiln remains slightly below the ambient pressure so that no fugitive emissions escape to the lab. Pressure transducers (K4) on each side of the load verify this. Air from outside the laboratory is supplied to the kiln (K6) and its temperature and relative humidity are measured with a thermocouple and a General Eastern Model G-Cap-V sensor, respectively.

The exhaust system consists of a heated line (F1) which leads to two sets of condensers (F2, F3) which cool the air and condense water. The water is collected in two-liter flasks (F4, F5) which are periodically weighed and emptied. The entire system is sloped toward the flasks. A third flask (K5), located at the low point in the kiln, was weighed emptied simultaneously; however, it only contained water when the kiln was operated at high relative humidity. A chiller (F8) supplies fluid for cooling the condensers as well as the cold water bathes containing the flasks. Temperature is measured before and after each set of condensers. After the condensers, the air passes through a flow controller (F6), a pump (F7), and is exhausted. The flow controller modulates the exhaust based on the control signal which would normally operate vents and control the wet-bulb temperature in the kiln.

A second heated line (S1) leads to a J.U.M. Model 3-200 total hydrocarbon analyzer (THA) (S2) which draws a constant 3 l/min gas sample from the kiln and uses an FID to measure its hydrocarbon concentration. Grade 5 nitrogen (S3) is used as a zero gas and certified 888 ppmv propane in air (S5) as a span gas for calibration of the THA. Instrument grade hydrogen (S4) is the combustion gas for the THA. A calibration procedure was followed every two to eight hours in which the instrument zero and span were checked. The maximum drift observed was 2% over a six-hour period.

Wood Collection

Freshly-sawn, nominal 2-by-6-inch by 8-foot (actual 4.2 x 14.7 x 249 cm) Douglas-fir lumber from the Coast range in Oregon was obtained in May and July
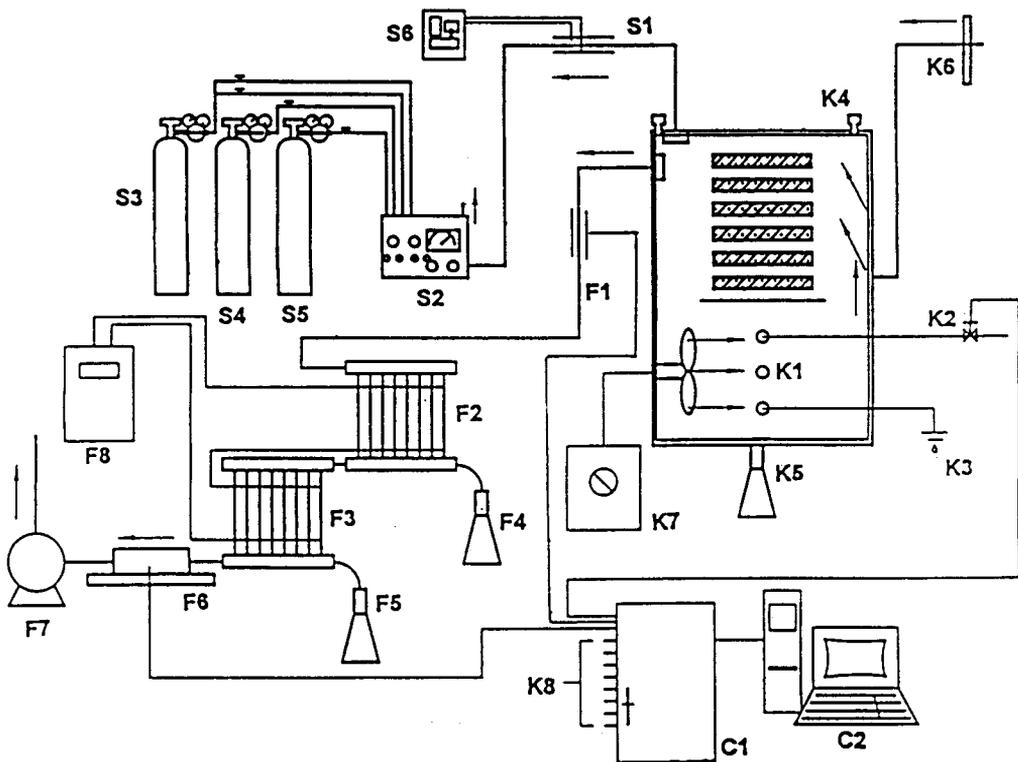
FIGURE 1. Equipment use for drying showing heating coils (K1), steam control valve (K2), condensate return (K3), pressure sensor (K4), drain (K5), inlet air (K6), fan controller (K7), thermocouples (K8), heated sampling line (S1), total hydrocarbon analyzer (S2), gas cylinders (S3, S4, S5), temperature controller (S6), control panel (C1), computer (C2), heated sampling line (F1), condensers (F2, F3), water collection flasks (F4, F5), flow controller (F6), pump (F7), and chiller (F8).

(Figure 2). The lumber was wrapped in plastic when not being processed. After transporting to Oregon State University, approximately four inches was cut from each end of each piece and discarded. This was done to reduce any effects due to evaporation from the ends of the lumber. The remaining portion was cut in half and each half placed on one of four piles. Each pile contained boards with different quantities of knots. Knots were used as the sorting criterion because there is evidence (Ingram et al. 1995b) that they significantly affect emissions. Each charge of lumber contained 20 of the 44-inch boards, five from each pile, so that the knots were as uniformly distributed as possible among the charges. All charges were individually wrapped in plastic and stored at -20°C until needed. Prior to its use in an experiment, a package of wood was thawed while covered to prevent evaporation.

Drying schedules were centered around those typically found in industry. A constant dry-bulb temperature of 160°F, 180°F, or 200°F (71.1°C, 82.2°C, and 93.3°C) was held after a warm-up period of approximately two hours. At each temperature, the wet-bulb depression was the same during each schedule step so that the relative humidity was similar at any point in time. Similarly, the effect of relative humidity was tested at 180°F (82.2°C) by using three different schedules for wet-bulb depression. Table 1 shows the five schedules and the number of replications of each.
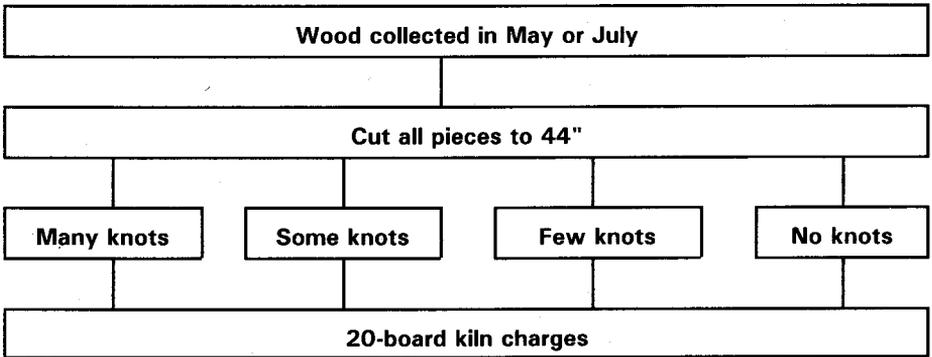
Wood collected in May or July

Cut all pieces to 44"

Many knots	Some knots	Few knots	No knots

20-board kiln charges

FIGURE 2. Sorting and cutting procedure.

TABLE 1. Drying schedules. The dry-bulb temperature was constant for any schedule. Read to the right of the dry-bulb temperature to find the number of charges at that dry-bulb temperature. The wet-bulb depression schedule is in the same column in the lower portion of the table.			
Dry-bulb temperature, °F (°C)	Number of Charges		
200 (93.3)		3	
180 (82.2)	2	5	2
160 (71.1)		3	
Time, hours	Wet-bulb depression, °F (°C)		
0-24	20 (11.1)	15 (8.3)	10 (5.6)
24-36	25 (13.9)	20 (11.1)	15 (8.3)
36-48	35 (19.4)	30 (16.7)	25 (13.9)
48-dry	45 (25.0)	40 (22.2)·	35 (19.4)

Drying a Charge

Each board was weighed and loaded into the kiln on 3/4" (1.9 cm) stickers to form a charge of lumber two boards wide and 10 rows high. It took approximately two hours for the dry-bulb and three hours for the wet-bulb temperatures to reach their respective set points. As necessary, the flasks (F4, F5, and K5 in Figure 1) were weighed and emptied. Temperatures, hydrocarbon concentration, and flow, and other experimental variables were recorded every three minutes. Drying times ranged from 68 to 86 hours and were typically about 72 hours. Our goal was to be sure the lumber was at a moisture content less than 10 percent, rather than a specific target moisture content. At the end of drying each board was weighed, oven dried, and reweighed.

Calculations

The overall calculation procedure (Table 2) was to obtain the dry gas flow rate through the kiln and use the concentration as measured by the THA to calculate an emissions rate. Integration of this emissions rate from the beginning of the drying cycle to any time or moisture level then gives the total emissions. The absolute humidity in and out of the kiln were also used with the dry gas flow rate and the mass of water emptied from the flasks to calculate the water loss rate from the wood. Integration of the water loss rate from the beginning of the drying cycle to the end should equal the weight loss from the boards (ignoring evaporation from the wet-bulb sock).

Calculations were done on the inlet flow stream (A1 in Figure 1), the 3 l/m flow stream to the THA (S1), and the vent flow stream (F1). The absolute humidity

THA Steam

T_d | T_w | Volumetric wet gas flow rate, V_{THA}

p_w^0 and Y_w^s

Vent Stream

T_{c2} | Volumetric wet gas flow rate, V_{vent}

p_w^0

Inlet Stream

T_{Inlet} | ψ_{Inlet}

p_w^0

Absolute humidity, Y_{THA}

Absolute humidity, Y_{vent}

Absolute humidity, Y_{Inlet}

Dry gas to FID, G_{THA}

Dry gas vented, G_{vent}

Water Collected

Hydrocarbon concentration from THA, y_H

Dry gas flow rate through kiln, G_{inlet}

Ovendry weight of wood

Rate of hydrocarbon emission, G_H

Net rate water leaving kiln

Board weight in

Board weight out

Time

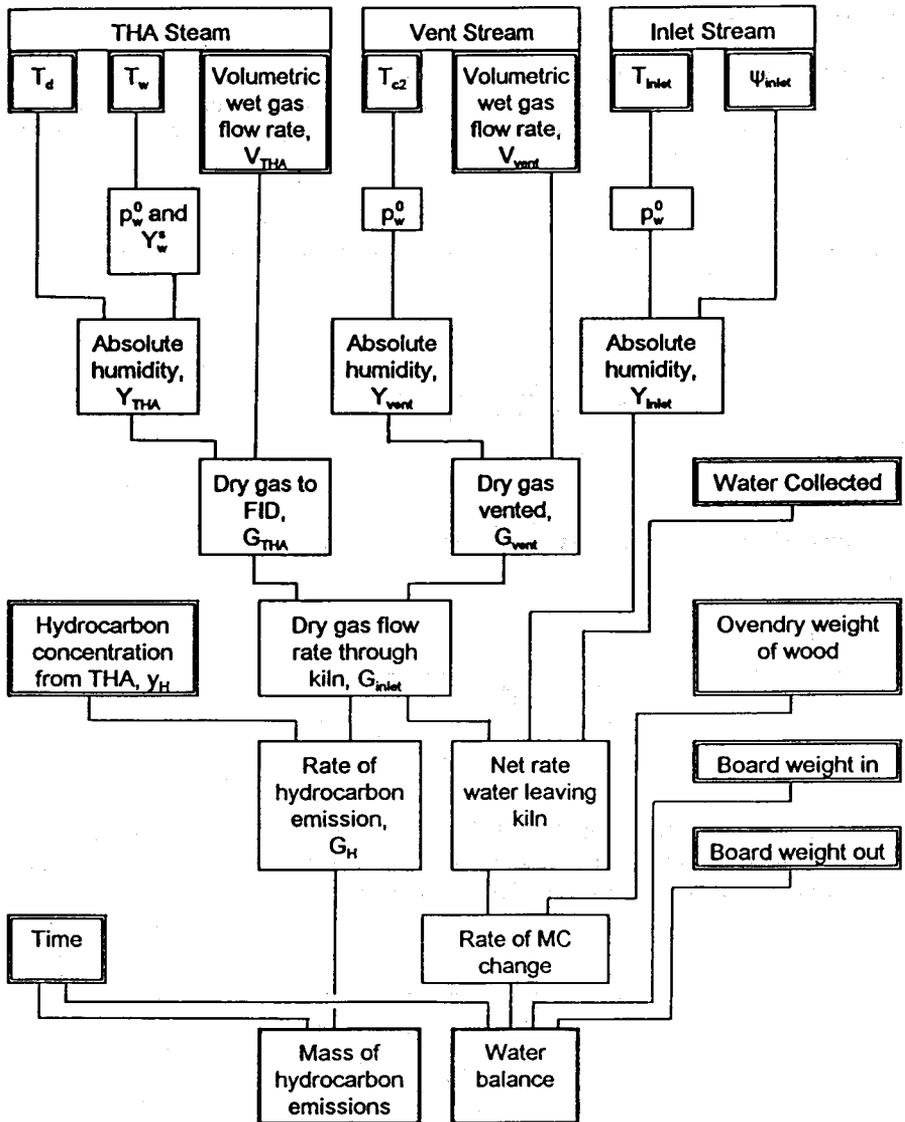Rate of MC change

Mass of hydrocarbon emissions

Water balance

TABLE 2. Calculation procedure. Measured variables have a double border, calculations a single border, and the results, a bold border.

and hydrocarbon concentrations in the kiln, vent stream, and stream to the THA are the same because the kiln is a well-mixed vessel. The steps in these calculations are outlined below.

Absolute humidity

Vapor pressures were calculated for each stream and in the kiln (Yaws, 1977). Here, T is the temperature leaving the second condenser set for the vent stream, the inlet air temperature for the inlet stream, and the kiln temperature for the kiln and the stream to the THA.

$$f(T) = 16.373 - \frac{2818.6}{T + 273.16} - 1.6908 \log (T + 273.16) - 0.0057546 \cdot (T + 273.16) + 4.0073 \cdot 10^{-6} \cdot (T + 273.16)^2$$

$$P_w^0 = \frac{101325 \ Pa}{760 \ mmHg} \cdot 10^{f(T)} \qquad\qquad 1$$

The basic definitions of relative humidity and absolute humidity were combined to give

$$Y_{vent} = \frac{M_w}{M_g} \cdot \frac{1}{\dfrac{p}{\Psi_C \cdot p_w^0} - 1} \qquad\qquad 2$$

where $p = 101{,}325$ Pa, $\Psi_C = 100\%$, and p_w^0 was calculated based on the temperature leaving the second condenser set where the gas had been cooled well below its dew point and was at 100% relative humidity. Similarly,

$$Y_{inlet} = \frac{M_w}{M_g} \cdot \frac{1}{\dfrac{p}{\Psi_{inlet} \cdot p_w^0} - 1} \qquad\qquad 3$$

where $p = 101{,}325$ Pa, Ψ_{inlet} was measured by the relative humidity sensor, and p_w^0 was calculated based on the temperature of the entering air.

For the stream to the THA, the absolute humidity was calculated based on the dry- and wet-bulb temperatures in the kiln (Treybal, 1980).

$$Y_{THA} = Y_w^s - \frac{(T_d - T_w) \times \dfrac{h_G}{k_y}}{\Delta H} \qquad\qquad 4$$

For the air-water system, $h_G/k_Y = 0.95$ kJ/(kg·K).

Gas flow rate

The volumetric gas flows were converted to a dry gas mass flow rate in four steps. First, the wet gas volumetric flow rate was converted to a molar basis. Second, the molal humidity was calculated from the absolute humidity. Third, the dry molal gas flow rate was calculated from the values in steps one and two. Finally, this was converted to a mass basis by multiplying by the molecular weight of air. These four steps can be combined to give

$$G_{vent} = \frac{V_{vent}}{V_0 \cdot \left(\dfrac{1}{M_g} + \dfrac{Y_{vent}}{M_w}\right)} \qquad\qquad 5$$

and

$$G_{THA} = \frac{V_{THA}}{V_0 \cdot \left(\dfrac{1}{M_g} + \dfrac{Y_{THA}}{M_w}\right)} \qquad\qquad 6$$

The inlet dry gas flow rate is obtained by adding the dry gas flows leaving the kiln

$$G_{inlet} = G_{vent} + G_{THA} \qquad\qquad 7$$

Cumulative THC and unit emissions

The THA reading was converted from a mole fraction to a mass ratio using the molecular weights of each component. The rate of emissions was then calculated as

$$G_{HI} = \frac{y_{H\,i} + y_{H\,i+1}}{2} \times \frac{M_p}{M_g} \times \frac{(G_{vent\,i} + G_{THA\,i}) + (G_{vent\,i+1} + G_{THA\,i+1})}{2}$$

8

The cumulative emissions were calculated as

$$m_H = \sum_{i=1}^{n-1} G_{H\,i} \cdot (t_i - t_{i-1}) \qquad\qquad 9$$

where n is time the index that corresponds to a board moisture content of 12 percent. This moisture content was selected to provide a common basis for comparison of total emissions among the charges since it would be nearly impossible to dry each charge to exactly the same moisture content without opening the kiln. A moisture content of 12 percent was selected because the average final moisture content of Douglas-fir lumber is often between 12 and 15 percent. The unit emisisons, E_{cum}, were calculated by dividing the cumulative emissions by the mass of wood in the kiln.

$$E_{cum} = \frac{m_H}{m_{OD}} \qquad\qquad 10$$

Water balance and board moisture content

The water entering or leaving the kiln in each stream was calculated by multiplying the dry gas flow rates by the absolute humidity. These were integrated over time to obtain the mass of water leaving the kiln. The board moisture fraction at any point during drying was then calculated as

$$X = X_o - \frac{m_{vent} + m_{THA} + m_C - m_{inlet}}{m_{OD}} \qquad\qquad 11$$

The time interval for emptying water from the condensers was much greater than the data logging interval. Therefore, linear regression between the natural log of moisture fraction and time was performed to allow m_{inlet} to be determined for each index i. The index, n, corresponding to 12 percent moisture content was determined by interpolation on the MC-time curve.

For each charge and overall water balance was calculated as

$$F_{bal} = \frac{m_{vent} + m_{THA} + m_C - m_{inlet}}{\Delta m_{wood}} \qquad\qquad 12$$

where a value for F_{bal} less than one indicates that less water was measured leaving the dryer than would be expected based on the weight change of the wood.

Statistical Analysis

The wood properties, sapwood, density, knot area, and ring count were compared among the 15 charges using an analysis of variance and a Tukey multiple comparison test. A stepwise multiple regression was used to determine which of the independent variables, dry-bulb temperature, wet-bulb depression, knot area, density, initial moisture content, and sapwood percentage significantly affected the dependent variable, unit emissions.

Results and Discussion

Wood used

The average wood properties for the experiments are shown in Table 3. These were not significantly different between the wood obtained in July and that obtained in May. An ANOVA showed that there were no significant differences among the charges in knot area, as expected based on the board sorting method used. In addition, there were no differences among the charges in sapwood percentage. Average charge density fell into two groups based on a Tukey test. One charge had a density which was significantly lower (458 kg/m^3) than the Tukey grouping for the other 14 charges and two charges were higher (520 and 528 kg/m^3, respectively) than the Tukey grouping for the other 13 other charges.

TABLE 3. Wood properties for the boards in the study				
Property	Mean	Std. Dev.	Maximum	Minimum
Sapwood, %	50.6	34.0	0	100
Density, kg/m^3	494	51	365	635
Knot area, in^2/board face	1.67	1.61	0	15.2
Ring count, /in.	6.0	2.5	2	17

Water balance

F_{bal} ranged from 1.04 to 1.07 indicating very good consistency in the measuring technique from charge to charge. Since the objective of this work was to determine the effect of temperature and relative humidity on the drying schedule, the consistency from charge to charge is very important. Less than one percentage point of this error can be attributed to evaporation from the wet-bulb sock. The rest is likely due to errors in the measurement of relative humidity of the inlet gas or the gas flow rate.

Emissions release

Typical hydrocarbon concentrations in the exhaust air ranged from 80 ppmv to 1500 ppmv as propane, depending on schedule and time in the schedule.

Background air, when sampled with the THA, contained 1 to 2 ppmv. We did not attempt to measure this continually, nor was it subtracted from the measured emissions.

The highest concentration in the exhaust air was observed during the early part of the drying schedule (Figure 3). The concentration steadily increased during the first two to four hours when air was not being pulled from the kiln through the vent line. During this period the rising temperature would have caused an increase in the vapor pressure of the organic compounds, also contributing to the increasing concentration. After the wet-bulb temperature reached set-point and sit and air was removed through the vent line, the hydrocarbon concentration rapidly decreased.

The rate of emissions (Figure 4) was also low during the warm-up period, while only 3l/min were removed in the FID stream. This method of heat-up is typical of many western kiln operations in which steam spray is not used except during conditioning. Cumulative emissions (Figure 4) are indicative of the changing release rate, increasing rapidly at first, then at a slower rate as the schedule progressed. Often, 80 percent of the emissions were released in the first half of the kiln schedule. Changes in the emissions rate are evident at 24, 36, and 48 hours when the wet-bulb temperature was lowered.

The wood collected in May and July had very similar emissions, averages of 0.42 and 0.43 g/kg_{ODwood}, respectively. Because of this, and the similarity in wood properties, the data was combined into one set and the remainder of the analysis will not distinguish between the May and July wood.

Factors affecting emissions

The cumulative emissions for each charge from green to a 12% final moisture content are shown in Table 4. Initially two charges were run at each of the non-center conditions. At that time in the experiment it appeared that there might be a temperature effect but no relative humidity effect. Therefore, the remaining wood was used for one additional charge at the high and low temperature conditions.

TABLE 4. Cumulative emissions (g/kg_{ODWood}) for each charge. The average at each condition is shown in bold.

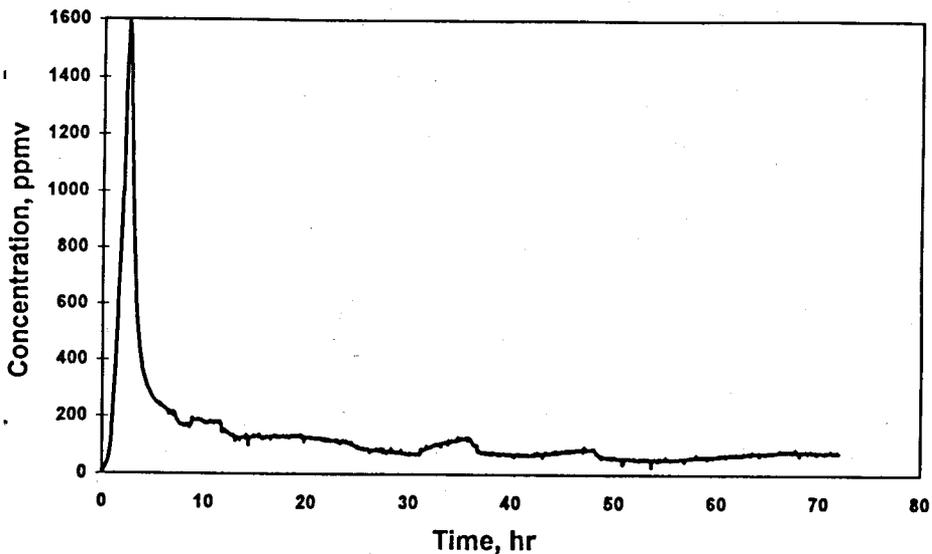| Initial dry-bulb temperature, °F (°C)	Initial wet-bulb depression, °F (°C)		
	10 (5.5)	15 (8.3)	20 (11.1)
200 (93.3)		0.30, 0.33, 0.32 **0.32**	
180 (82.2)	0.35, 0.43 **0.39**	0.34, 0.56, 0.51, 0.46, 0.49 **0.47**	0.47, 0.37 **0.42**
160 (71.1)		0.46, 0.50, 0.43 **0.46**	

FIGURE 3. Concentration in ppmv as propane versus time for a charge dried at 180∘F (82.2∘C) and an initial wet-bulb depression of 15∘F (8.3∘C).
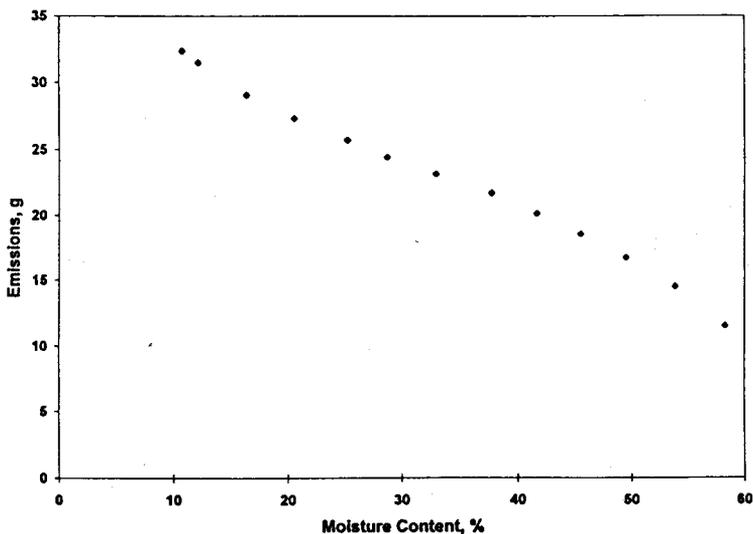

FIGURE 4. Rate of emission s release and cumulative emissions versus time for a charge dried at 180∘F (8.2.∘C) and an initial wet-bulb depression of 15∘F (8.3∘C).

A stepwise regression incorporating the wood variables as well as dry-bulb temperature and wet-bulb depression (Table 5) indicated that dry-bulb temperature and initial moisture content were the significant variables. These are related by

$$E_{cum} = 0.556 - (0.0059 * T_d) + (0.0066 * X_o) ; \quad r^2 = 0.66$$

(13)

TABLE 5. Results of stepwise regression on all wood and kiln variable. The r-squared for the model is 0.66.

	DF	Sum of Sq.	Mean Sq.	F	Prob > F
Regression	2	0.0603	0.0302	11.74	0.0015
Error	12	0.0308	0.0026		
Total	14	0.0912			
				.	
Variable	Parameter Estimate	Standard Error	Type III Sum of Sq.	F	Prob > F
Intercept	0.741	0.213	0.031	12.09	0.0046
Dry-bulb	-0.0033	0.001	0.025	9.98	0.0082
Initial MC	0.0066	0.002	0.028	10.93	0.0063

This indicates that the emissions increased by 0.0066 g/kg_{ODwood} for each percent increase in charge initial moisture content. Also, the emissions were reduced by 0.0033 g/kg_{ODwood} for each Fahrenheit degree (0.0059 g/kg_{ODwood} for each Centigrade degree) of temperature increase.

Other variables, such as change in moisture content or water loss, could have been used in this analysis rather than initial moisture content; however, we elected to present initial moisture content because of its simplicity. Presenting this analysis based on change in moisture content would only result in a different constant because the unit emissions for each charge have been reported at a 12% final moisture content. Water loss is a slightly better predictor of emissions; however, it is much more difficult to calculate and apply in a practical sense.

Figure 5 shows a typical plot of cumulative emissions versus moisture content for drying at the center condition. After the initial heat-up period and high emissions rate during the first few hours of venting, there was a nearly linear relationship between moisture content and cumulative emissions. The authors do not imply that
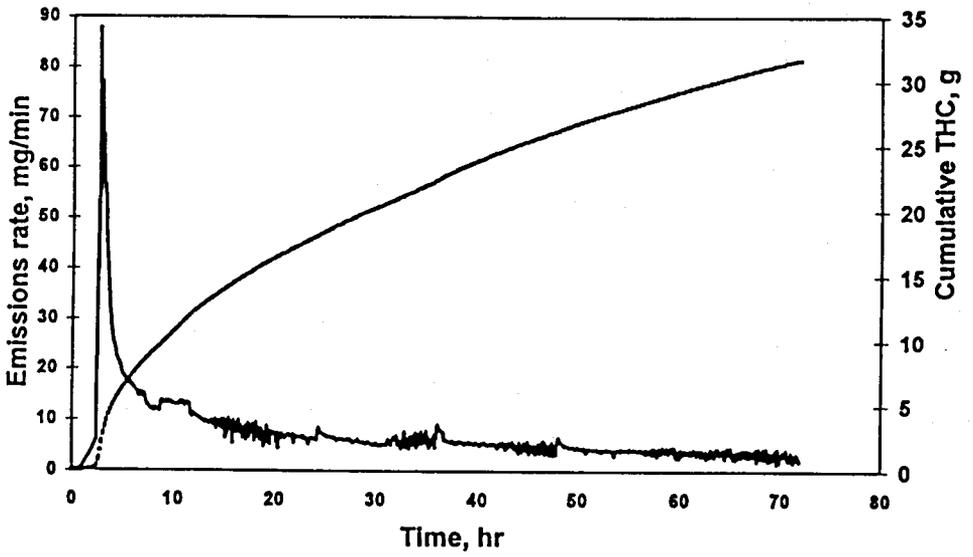
FIGURE 5. Emissions as a function of charge moisture content for a charge dried at 180°F (82.2°C) and an initial wet-bulb depression at 15°F (8.3°C)
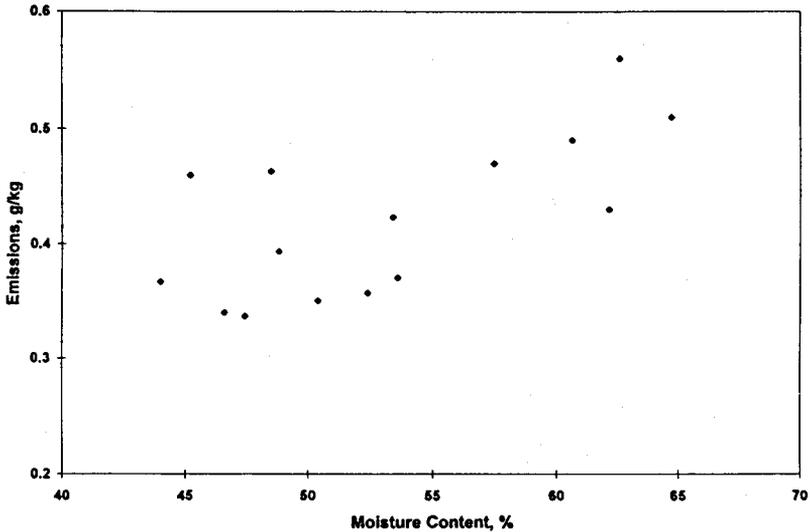

FIGURE 6. Emissions versus initial charge moisture content. Data has been adjusted to a dry-bulb temperature of 180°F (82.2°C).
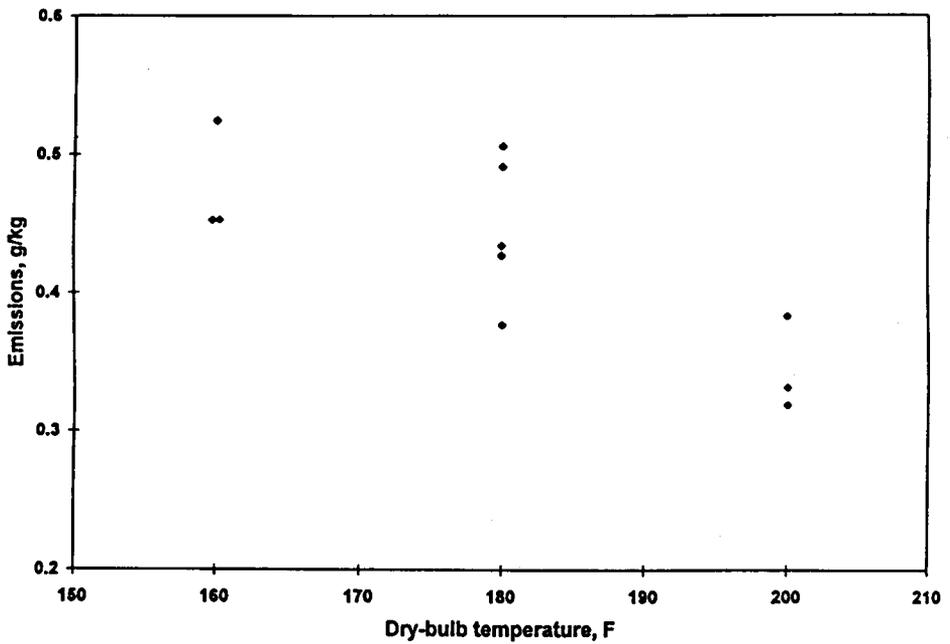
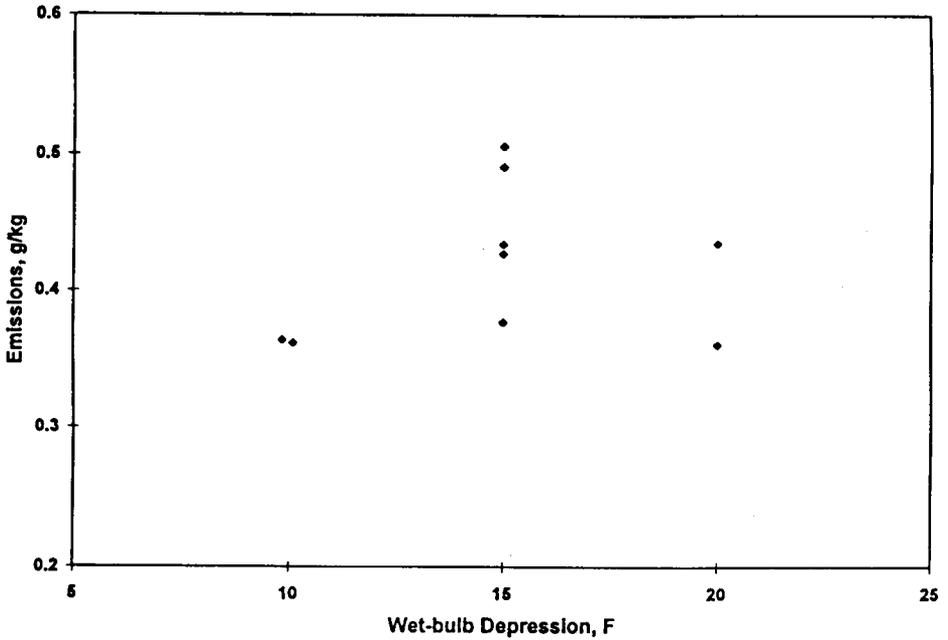FIGURE 7. Emissions versus temperature. Data has been adjusted to an initial moisture content of 52.2%.

FIGURE 8. Emissions versus initial wet-bulb depression. Data has been adjusted to an initial moisture content of 52.2%.

this is a cause-and-effect relationship; however, it may allow mills to adjust emissions estimates as final moisture content requirements change.

Figure 6 shows the data from Table 4 adjusted for the effect of drying temperature using

$$E_{ad} = E_{cum} - 0.0059 * (82.2 - T_d) \qquad 14$$

where 180°F (82.2°C) is the temperature to which the data were adjusted. Thus, Figure 6 shows values that would be expected if every charge had been dried at 180°F. It is clear that emissions increase as initial moisture content increases within the experimental range. A 10 percent increase in the initial moisture content, from 52 to 62% for example, is likely to result in a 13% increase in emissions. The percent sapwood in each charge was related to the charge moisture content; however, the sapwood percentage was not a significant factor according to the stepwise regression. In further research it would be interesting to dry sapwood and heartwood charges to compare the emissions.

Figure 7 shows the data at an initial wet-bulb depression of 15°F from Table 4 adjusted for initial moisture content. Each value in Table 4 was adjusted for initial charge moisture content using

$$E_{ad} = E_{cum} + 0.0066 * (52.2 - X_o)$$

where 52.2 percent is the average initial moisture content for all charges combined. Thus, Figure 7 shows values that would be expected if every charge had an initial moisture content of 52.2 percent. It is clear that emissions are reduced as dry-bulb temperature increases for Douglas-fir within the experimental range. A 20°F (11.°C) increase in dry-bulb temperature, from 180°F to 200°F for example, is likely to result in a 15% decrease in emissions. It is unlikely that this relationship will continue indefinitely as temperature increases because it is known, for example, that the emissions are higher from veneer drying (Plywood Research Foundation, 1971). Ingram found no difference in the emissions from Southern pine at 180°F and 245°F.

There is no obvious reason why emissions are less at the higher temperature, but one can postulate several explanations. At lower temperatures, the surface of the board might dry later because a less significant moisture content gradient develops. As a result of the lower moisture content gradient, more free water can move to the surface of the board and carry with it more of the organic compounds. The reduced venting of the kiln at higher operating temperatures may be another explanation. Absolute humidity increases with temperature at a given wet-bulb depression and the make-up air requirements for the kiln are reduced. Less air exchange means that a higher concentration of organics are present in the kiln atmosphere and there is then a smaller concentration difference between the airstream and the wood. The mass transfer from the surface of the wood to the air depends on the concentration difference of an individual chemical species and as

it is reduced, the rate at which organic compounds leave the wood may be reduced. Yet another possibility is that chemical reactions occur at the higher temperatures that cause polymerization of the monoterpenes. Determination of the actual mechanism causing emissions to decrease with temperature would, no doubt, be a difficult research assignment.

There is no difference in the emissions among the charges dried at 180°F (82.2°C) with different wet-bulb depressions (Figure 8). Thus, the results indicate that the relative humidity in the kiln does not affect the emissions. This means that a source test conducted at a given temperature should be valid over a range of relative humidities.

The total emission level of 0.47 g/kg_{ODwood} can be expressed as pounds per thousand board feet if assumptions are made about the size and specific gravity of the wood. For example, if one assumes a target size of 5.8" (14.7cm) by 1.65" (4.2 cm) and a basic specific gravity of 0.45 (1.87 lbs wood/ nominal board foot), the emissions become 0.85 lbs/mbf. For comparison, NCASI reported 0.14 g/kg_{ODwood} for Douglas-fir sapwood, 0.22 g/kg_{ODwood} for Coastal Douglas-fir, and 0.43 g/kg_{ODwood} for Douglas-fir heartwood. Ingram et al. (1995b) reported approximately 2.75 g/kg_{ODwood} on southern pine while the same NCASI study only reported 1.02 and 1.53 g/kg_{ODwood} for loblolly pine from Arkansas and Texas, respectively. The NCASI work was done on a 1000 bf kiln while the works of Ingram and the present work were done on smaller kilns.

Conclusions

During a typical drying schedule at a dry-bulb temperature of 180°F (82.2°C) and an initial wet-bulb depression of 15°F (8.3°C), producers can expect the total hydrocarbon emissions from Douglas-fir lumber to be about 0.47 g as propane per kg of oven-dry wood. On a volume basis, this corresponds to approximately 0.85 pounds per 1000 nominal board feet. Most of the hydrocarbon emissions occur during the first half of the drying period, with the maximum emission rate occurring when the kiln first begins to vent.

Within the range of dry-bulb temperatures typically used by industry (160 to 200°F), higher temperatures should lead to lower total hydrocarbon emissions from Douglas-fir lumber. This is unaffected by the initial wet-bulb depression within the range typically used by industry (10 to 20°F).

Greater moisture content change or greater water loss during drying results in greater total hydrocarbon emissions from Douglas-fir lumber. However, this study was not designed to explore the effects of wood properties on the quantity of emissions.

The information obtained in this study should be useful to those interested in estimating total hydrocarbon emissions and how they vary with kiln conditions.

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NOMENCLATURE

E	unit emissions g/kg_{ODwood}
F_{bal}	mass balance factor, -
G	mass flow rate of dry gas, kg/s
G'	molal flow rate of gas, mol/s
G_H	mass flow rate of hydrocarbon, kg/s
ΔH	latent heat, 2419.3 kJ/kg
h_G	convective heat transfer coefficient, $W/m^2 \cdot K$
k_Y	convective mass transfer coefficient, $kg/m^2 \cdot s$
m	mass, kg
M_g, M_w, M_p	molecular weights of air, water, and propane kg/kgmol
p	total pressure, Pa
p_g, p_w	partial pressure of dry gas and water vapor, Pa
P_w^0	vapor pressure of water, Pa
t	time, s
T	temperature, C
T_d, T_w	dry- and wet-bulb temperatures in kiln, C
V	volume flow, m^3/s
V_o	standard volume, 22.4136 $m^3/kgmol$
X	moisture fraction, kg_w/kg_s
Y	absolute humidity, kg_w/kg_g
Y'	molal humidity, $moles_w/mole_g$
Y_w^0	absolute humidity of saturated gas at T_w, kg_w/kg_g
y_H	mole fraction of hydrocarbon (ppmv x 10^{-6})
ψ	relative humidity, fractional

additional subscripts

ad	adjusted for T_d or X_o
c	after the second condenser set , or all condensed water
cum	cumulative
H	hydrocarbon
i	time index
inlet	inlet stream
kiln	in kiln atmosphere
o	initial
THA	stream to total hydrocarbon analyzer
vent	stream to vent
wood	wood in kiln