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Amendments made to Title V of the Clean Air and Clean Water Act in 1990 are forcing emitters of volatile organic compounds, such as kiln installations, to obtain operating permits based upon the quantity and species of emissions produced. In this thesis two methods for determining total hydrocarbon emissions released in the hot humid exhaust of lumber dry kilns are compared. Emissions from both commercial and laboratory kilns are included.

The activated charcoal and condensation method provided speciated information about the monoterpenes in the exhaust as well as total hydrocarbon emissions, however not all volatiles in the exhaust were detected. The total hydrocarbon analyzer (THA) method detected most volatiles in the exhaust but did not provided speciated information. The average quantity of total hydrocarbons emitted during drying of 2x6 Douglas-fir lumber in a laboratory kiln, as measured with a total hydrocarbon analyzer, was 0.97 g/kg_{ODwood} (2.05 lbs/mbf). GC-MS analysis of extracted, adsorbed, and condensed volatiles identified α-pinene as the dominantly emitted monoterpene but only detected total monoterpene emissions of 22.7% of the total hydrocarbon emissions.

Matched charges of 2x6 inch Douglas-fir dried with the same schedule, as measured with a total hydrocarbon analyzer, showed that the commercial kiln emitted 1.07 g/kg_{ODwood} (2.05 lbs/mbf) while the laboratory kiln emitted an average of 0.99

g/kg_{ODwood}. This indicates that the laboratory kiln, running the same drying schedule, may be a representative model of a commercial lumber dry kiln. GC-MS analysis of the exhaust revealed α-pinene to be emitted in quantities 10 times higher than the other monoterpenes detected.

Total hydrocarbon emissions from matched charges of two-inch by random-width ponderosa pine released from a commercial kiln were measured at 2.82 g/kg_{ODwood} (5.20 lbs/mbf) while the laboratory kiln emitted an average of 1.97 g/kg_{ODwood}. This indicates that the laboratory kiln, running the same drying schedule, may not be a representative model of a commercial lumber dry kiln. GC-MS analysis of the exhaust identified β-myrcene and Δ-3-carene as the dominant species emitted, they had emissions an order of magnitude greater than the next most abundant emittant, β-pinene. Total hydrocarbon emissions were detected in quantities within 20% of the THA's measurement.

The use of this laboratory model is much more efficient than monitoring commercial kiln emissions because of its location, size of lumber charge, and proximity to laboratory analysis equipment. The small size of the lumber charge makes it possible to economically test various schedules quickly and to compare emission rates.

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Total Hydrocarbon Emissions from Lumber Dry Kilns

by

Mark Robert Lavery

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Mark Robert Lavery, Author

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NOMENCLATURE

A	constant, 0.79
D	thickness of oven dry samples, meters
E	constant, -6.649
G'	dry gas flow rate, kgmols/minute
G	dry gas flow rate, kg/minute
G_{CH}	dry gas flow rate in the adsorption sampling train, kgmol/minute
G_H	hydrocarbon emission rate, g/min
h_g/k_y	psychrometric ratio, kJ/(kg-K)
L	length of oven dry samples, meters
m_i	quantity of monoterpene in a given sample, mg
M_i	quantity of monoterpene collected, for a given time interval, mg
m_{OD}	oven dry weight of wood, kg
MW_{air}	molecular weight of air,
MW_{water}	molecular weight of water,
p	total pressure, Pa
P_w^0	vapor pressure, Pa
SG	specific gravity
T	temperature, °C
$THA_{moiscor}$	THA reading adjusted for humidity, ppmv as propane
$THA_{drybasis}$	THA reading on a dry gas basis, ppmv as propane
V_s	quantity of solvent used to extract samples, ml
W	width of oven dry samples, meters
x_i	raw values returned by GC-MS, mg/liter
x_u	undecane concentration returned by the GC-MS, g/liter
x'_i	raw values adjusted for detector response, mg/liter
X_O	initial moisture content
X	moisture content, %
y	absolute humidity, kg_{water}/kg_{air}
Y'	molal humidity, $kgmol_{(water)}/kgmol_{(air)}$
ρ_{H_2O}	density of water
λ	latent heat, kJ/kg
Ψ_C	relative humidity, %

TOTAL HYDROCARBON EMISSIONS FROM LUMBER DRY KILNS

CHAPTER I Introduction

Increasing human population, with its ever-growing need and desire for products, is leading to an increase in manufacturing. This increasing population is driving increased resource exploitation, while demanding 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 their 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. Pressure to maintain and improve air and water quality is forcing the industry to monitor and control emissions from these processes. Regulations and public attention are forcing the industry to address the issue of volatile organic compound (VOC) emissions by installing costly emission control technologies.

The lumber drying industry has great interest in the amount of hydrocarbon being emitted from their drying process because of the expense of EPA Title V permitting issues. The Clean Air Act (CAA) states that it is necessary to describe dry kiln emissions such that potential Hazardous Air Pollutants (HAP) sources as well as benign VOC emission sources to be identified and subsequently monitored, regulated, and controlled. HAPs are chemicals that cause serious health and environmental effects including; cancer, birth defects, nervous system disorders, and even death.

The lumber drying industry as a whole has little to no scientific information on the quantity of emissions that are being released from their processes. This ignorance and the fear of noncompliance are forcing kiln operators to obtain Title V permits based upon quantities of emissions that are potentially greater than they actually produce. Until recently (Ingram et al., 1995a; NCASI, 1996; Wu, 1997), in fact, there are no published studies detailing the emission quantity from commercial kilns. This

thesis directly addressed this data void by monitoring the emissions from a commercial kiln.

Increasingly, states are asking for speciated VOC information in addition to total hydrocarbon measurements. There are no published studies describing the emission spectra expected in the exhaust. It is believed that a major component of the emissions released during lumber drying are monoterpenes ($C_{10}H_{16}$) which are the substances our noses identify as the smell of wood. The major monoterpenes (α-pinene, d-limonene, and β-pinene) are expected to be emitted from a kiln during the peak drying rate of the kiln schedule (McDonald & Wastney, 1995; Wu, 1997), i.e. during the initial six hours of the schedule (Ingram et al., 1995a; Wu, 1997).

Monitoring a commercial kiln is time consuming, logistically difficult, and thus expensive. This thesis addressed the issue of kiln drying capacity and expected emission rates. The emissions from two commercial kilns and those from Oregon State University's Forest Research Laboratory's laboratory kiln were compared using the same monitoring equipment, methods, and matched lumber. Douglas-fir and ponderosa pine emissions were investigated in this thesis.

This thesis is composed of three manuscripts for publication. The first manuscript (Chapter II), *A Methods Paper: Charcoal Adsorption of VOC vs. a Total Hydrocarbon Analyzer,* investigates the relationship between the total hydrocarbons (THC) and speciated monoterpene emissions detected from matched charges of 2x6 Douglas-fir (*Pseudotsuga menziesii*) dried in a laboratory kiln. The second manuscript (Chapter III), *VOC Emissions from Douglas-fir: Comparing a Commercial and a Laboratory Kiln*, investigates the relationship between the THC emissions released from a commercial kiln and a laboratory kiln. This study employed matched charges of 2x6 Douglas-fir. The third manuscript (Chapter IV), *VOC Emissions from Ponderosa Pine: Comparing a Commercial and a Laboratory Kiln*, investigates the relationship between the THC emissions released from a commercial kiln and a laboratory kiln. This study employed matched charges of random width ponderosa pine (*Pinus ponderosa*). GC-MS analysis of the emissions from representative charges was conducted for all three studies.

The objectives of this thesis were to measure and speciate the monoterpenes in the exhaust gas released while kiln drying Douglas-fir and ponderosa pine. At the same time, measurements of the total hydrocarbons being emitted were measured. The third objective was to compare both the monoterpene emissions and the total hydrocarbon measurements from the commercial and laboratory kilns.

A strong understanding of the emissions pattern and the relationship between commercial scale kilns and Oregon State University's laboratory kiln, will provide a great service for the industry. The laboratory kiln's small scale and highly controlled environment are ideally suited to test a diverse species set and drying schedule library efficiently and economically.

CHAPTER II A Methods Paper

Charcoal Adsorption of VOC vs. a Total Hydrocarbon Analyzer

Abstract

Amendments made to Title V of the Clean Air and Clean Water act in 1990 are forcing emitters of volatile organic compounds, such as kiln installations, to obtain operating permits based upon the quantity and species of emissions produced. The quantity of total hydrocarbons (THC) emitted during drying of 2x6 Douglas-fir (*Pseudotsuga menziesii*) lumber, dried in a laboratory kiln, was measured with a total hydrocarbon analyzer (THA). The average total hydrocarbon emissions from two matched charges was 0.97 g/kg_{ODwood} (2.05 lbs/mbf). GC-MS analysis of extracted condensate and volatiles adsorbed onto activated charcoal identified α-pinene as the dominantly emitted monoterpene. Comparisons between the THA measurements of total emissions and those detected by condensation and adsorption with activated charcoal showed the monoterpene emissions to be 22.7% of the total hydrocarbon emissions[1].

[1] The author wishes to acknowledge Frank Lumber of Mill City OR. for assistance on the project. This work was funded by USDA Competitive Grant 95-37500-2302.

Introduction

The continuing growth of the human population is fueling increased forest products manufacturing globally. This increasing population is driving increased resource exploitation, while demanding good air, water and scenic quality. Manufacturers in the forest products industries are caught in the middle of this seeming contradiction. People require quality forest products for new homes and their furnishings while demanding no visible sign of the processes required to supply those finished forest products. The lumber manufacturing industry seems to cross the 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 its emissions.

A major component of the emissions released during lumber drying are volatile organic compounds (VOC)(Noyes, 1991), hydrocarbons. Monoterpenes ($C_{10}H_{16}$) are expected to comprise a major portion of the total hydrocarbon (THC) emissions. Monoterpenes are those substances our noses identify as the smell of wood. The majority of the monoterpenes (α-pinene, β-pinene, and limonene) emitted are expected to be released from a kiln during the peak-drying rate of the kiln schedule (McDonald & Wastney, 1995; Wu, 1997), after the warm-up period when venting begins (Ingram et al., 1995a; Wu, 1997).

A better understanding of the quantities and identities of emission components will help companies in the process of permit acquisition by detailing the chemical constituents expected to be found in emissions. This understanding may eventually lead to improved methods of kiln operation and emission control while retaining the ability of kiln operators to dry lumber economically.

The primary objective of this study was to develop a method to identify the most abundant monoterpenes emitted from a lumber dry kiln as the lumber is dried. The secondary objective was to obtain both qualitative and quantitative results with a single method. The tertiary objective was to compare quantitative information from

the monoterpene portion of the study with quantitative results obtained by a total hydrocarbon analyzer (THA).

Literature Review

Volatile Organic Compounds

The U.S. Environmental Protection Agency (U.S. EPA, 1994) classifies VOC simply as substances that contain the element carbon (C) and that may be precursors to smog and ozone (O_3) formation (U.S. EPA, 1993). VOCs are emitted into the atmosphere from many different sources which may be biogenic (produced by action of living organisms by processes essential to life and its maintenance) or anthropogenic (induced alterations on nature as a result of human presence or activities). Typically we accept biogenic emissions as being natural and therefore acceptable while emissions from anthropogenic sources, such as sawmills, are considered "unnatural" and therefore pollutants. Regulations and public attention are forcing the industry to address the issue of VOC emissions by installing often-expensive emission control technologies.

A potentially significant source of VOC emissions from a sawmill is the exhaust of lumber dry kilns. Consequently air pollution is a byproduct of forest products manufacturing (Engelberg, 1995). These compounds are anthropogenic and deemed pollutants even though they are also emitted biogenically and are common in the environment.

α-pinene is predicted to be the dominantly emitted species in the kiln exhaust (Banerjee et al., 1995). Other monoterpenes commonly found in the ambient air around coniferous trees, such as; β-pinene, Δ-3-carene, camphene and d-limonene (Roberts et al., 1983), might be detected in lumber dry kiln exhaust. Softwoods emit a larger quantity of VOCs than hardwoods (Grzanka, 1995). Kiln drying lumber causes the wood to heat, which increases vapor pressure and thus promotes monoterpenes in the lumber to volatilize. As a gas, compounds can relatively easily migrate out of the

lumber and into the ambient atmosphere. When lumber or veneer is heated, the wood resins become less viscous and may also flow as liquids from the inside of the lumber to the surface (Browne & Rietz, 1959; West, 1957; Milota, 1995). Extractives may also be transported to the surface of the wood by mass flow as water migrates to the surface of the lumber.

Squire et al. (1967) noted that the water-soluble wood extractives tend to increase in concentration from the pith to the bark, with an abrupt decline in concentration at the heartwood-sapwood boundary. Terpenes account for only a small fraction of the total mass of the wood and apparently play no significant structural role in the tree. However, since terpenes are the most volatile components of the extractives they account for the smell of cut lumber (Cronn et al., 1983). It is expected that lumber containing a larger percentage of heartwood will have higher emissions (Fraser & Swan, 1972).

Kiln exhaust may contain many different VOCs, 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 (Shigehara, 1969), and the species of lumber dried, since the chemical composition varies among species. Initial hypotheses indicate that emissions from kiln drying lumber may be a significant point source for VOCs. This is an interesting situation since trees naturally emit these suspect VOC (biogenic source) throughout their lives. Biogenic sources of VOC emissions are estimated to account for up to two thirds of total global VOC emissions (Müller, 1992). Therefore, biogenically emitted VOCs in the atmosphere potentially exceed those emitted from anthropogenic sources (Isidorov et al., 1985). Brown (1971) calculated that 250 acres of forest produce an equal quantity of volatile hydrocarbons as a typical plywood plant. The veneer dryer probably produces a greater quantity of VOCs per volume of wood than a lumber kiln because of higher dryer temperatures.

Biogenic VOCs photoreact (reaction occurring with the aid of solar energy) to form aerosols and ozone (Arnts & Gay, 1979; Gay & Arnts, 1977; Hatakeyama et al., 1989; Kotzias et al., 1990; Lillian, 1972; Pandis et al., 1991; Ripperton et al., 1991;

Roberts et al 1983; Westberg & Rasmussen, 1972; Zimmerman et al., 1978). Biogenically derived VOC likely photoreact in the same manner as the anthropogenic VOC emitted from kilns, since the chemical compositions are the same. One obvious difference between the biogenic and anthropogenic VOC is that the anthropogenic emissions are emitted from a concentrated point source, in this case the lumber dry kiln, into a local atmosphere that may have relatively high concentrations of other compounds, such as NO_x from fossil fuel burning. Alternately, the biogenically emitted VOCs are predominantly emitted from large tracks of forest in large expanses of unpopulated regions.

Lumber dry kilns are thought to have two main classes of emissions: particulates, solid materials of 10 μm or larger (U.S. EPA, 1993; Grzanka, 1995; Ingram et al., 1995a), and hydrocarbons (molecules composed entirely of carbon and hydrogen). Hydrocarbons, including diterpenes, hemiterpenes, and monoterpenes may readily condense into the sub-micron aerosol particles (Hatakeyma et al., 1989) responsible for "blue haze," or may remain volatile (Cronn et al., 1983; Brown, 1971). Diterpene (resin acids) hydrocarbons are readily condensable, while hemiterpene hydrocarbons are volatile, but less readily condensable. These, along with monoterpenes, are the expected classes of compounds in the exhaust from kilns operating at high temperature (Brown, 1971).

Information on the identification and quantification of the chemical composition of exhaust from commercial lumber kilns has not been published; thus lumber companies have little data describing their kiln emissions (Taylor & Ingram, 1995). Increasingly, states are asking for speciated VOC information in addition to total VOC. In addition, the Clean Air Act states that it is necessary to describe dry kiln emissions such that potential Hazardous Air Pollutants (HAP) sources may be identified and subsequently monitored, regulated, and controlled.

Volatile organics can be collected by sufficiently lowering the temperature of the media and thus condensing the volatiles. Volatiles in gaseous media can also be adsorbed onto solid adsorbents such as Tenax and activated charcoal. Condensed and adsorbed volatiles can then be extracted from the condensate or solid adsorbent using

various organic solvents such as dichloromethane (McDonald & Wastney, 1995; Yokouchi & Ambe, 1985). It is also possible to collected gas samples in Summa containers; where samples for analysis can be drawn directly form this trapped sample gas.

Activated charcoal in glass tubes has been used in many applications (paint spray booths, indoor air quality, ambient air samples) for collecting volatile compounds (Arey et al., 1991, Girman et al., 1984; Wadden et al., 1995). In order to analyze the adsorbed volatiles, the volatiles can be desorbed from the charcoal with organic solvents (Girman et al., 1984; Ruhl, 1993). Activated charcoal has a finite absorption capacity (Noyes, 1991) and thus should be replaced often to ensure breakthrough of volatiles is avoided.

The presence of water vapor tends to reduce the organic compound absorption rate onto activated charcoal if organics have concentrations less than1000 ppmv (parts per million). Organic concentrations above 1000 ppmv do not seem to be affected by water concentration (Noyes, 1991). Water is a polar molecule that has an affinity for the non-polar surface of the adsorbent (activated charcoal) and is a much smaller molecule than the compounds of interest. Therefore, water has the ability to out compete the organics of interest for the active binding sites (Gong & Keener, 1993; McInnes, 1995; Noyes, 1991).

Operation temperature also will have an effect upon carbon absorption performance. If temperatures are "excessive", organics may be lost or isomerized due to exothermic chemical reactions occurring on the carbon surface (Noyes, 1991). When exhaust streams are above 100 °C activated charcoal adsorption of VOCs has limited application (McInnes, 1995).

Gas Chromatography with Mass Spectrometry

Gas chromatographic mass spectrometry (GC-MS) is commonly used to identify and quantify a relatively small number of well-defined analytes in environmental samples (Gosh & Anderegg, 1989). Volatile organic compounds are

commonly desorbed from an adsorption media and analyzed with a GC-MS (Arey et al., 1991; Girman et al., 1984; Helmig et al., 1989; Isidorov et al., 1985; Jüttner, 1986; Kotzias et al., 1990; McDonald & Wastney, 1995; Wadden et al., 1995; Yokouchi & Ambe, 1985). The retention time and mass spectra have been defined for the VOCs of interest (Ghosh & Anderegg, 1989). Gas chromatography (GC) is the most widely used method for VOC analysis, because of its "excellent selectiveness, high sensitivity, and wide dynamic concentration range" (Klemp et al., 1994).

Sample Injection System

The sample is injected onto a glass liner within an electrically heated metal block, where it is vaporized and swept onto the column by the mobile phase. The block is heated to a controllable fixed temperature that is high enough to essentially instantly vaporize the liquid sample into a "plug" of vapor (Willard et al., 1988). To take full advantage of the separating power of the fused-silica capillary column, a narrow sample "plug" is necessary (Klemp et al., 1994). This is achieved with rapid vaporization of the sample.

Reduction in sample volume is usually required when using a capillary column. This may be achieved by using an injector-splitter, where usually a two-μL sample is injected but only 0.02-μL is swept into the capillary; the remainder is vented. This technique wastes a significant portion of the sample but is essential in order to prevent column overload and saturation (Willard et al., 1988).

To avoid a potentially large solvent tail, the injection port is vented to the atmosphere approximately 30 seconds after initial injection, at this time the majority of the solvent and essentially all the sample will have entered the column. Proper timing of the venting is critical; if the time is too short sample components may be lost, whereas if venting is delayed too long the solvent peak may be larger than necessary, potentially masking peaks of interest (Willard et al., 1988).

Automatic Sampler

An "auto-sampler" automatically duplicates manual sample measurements and injection. The auto-sampler flushes the syringe with each new sample in order to remove traces of each previous sample, new sample is then drawn into the syringe to wet the internal walls completely and to eliminate air bubbles. A precisely measured aliquot of sample is drawn and injected into the injector port of the gas chromatograph. Two of the many variables in gas chromatography are the sample injection volume and injection rate (Willard et al., 1988). The automatic sampler bypasses these problems with machine reproducible and consistently more precise injection than even the most skilled chromatographer.

Carrier Gas

Carrier gases transport the sample through the column to the detector. Column and detector performance are both affected carrier gas used. Helium and hydrogen are usually give a more linear detector response than nitrogen over a wider range of flow velocities making them the gases of choice (Willard et al., 1988).

Temperature Programming

Temperature programming is used to combine the best results of runs at different isothermal conditions. Samples are injected into the chromatographic system with the GC oven temperature set lower, preferably 90 °C lower, than that of the lowest-boiling component in the sample. The oven temperature is then raised at a pre-programmed heating rate. Earlier peaks, representing the low-boiling components, elute essentially when they would from a relatively low isothermal temperature schedule. As the temperature is ramped up, the high-boiling components are forced through the column with an ever-increasing rate. The final programmed temperature should be higher than the boiling point of the solute with the highest boiling point, assuming the maximum temperature limit of the stationary phase is not exceeded. As

the temperature ramps, individual compounds automatically "select their own" ideal temperature in which to migrate and separate within the column. If the column temperature is raised linearly, the members of any homologous series should elute in roughly equally spaced intervals (Willard et al., 1988). With even the most careful planning and operation complications invariably arise, such as overlapping peaks, these often result in incomplete resolution (Ghosh & Anderegg, 1989).

Mass Spectrophotometer

The quadrupole mass spectorphotometer (MS) is ideally suited for analysis of ionized VOC samples. Unknown sample mixtures are separated via the chromatographic column in the GC oven, into "slugs" of distinct individual compounds. The "slugs" are chronologically and independently ionized in a hydrogen flame. The ions then travel between four electrically conducting, parallel rods of the quadrupole mass analyzer. By ramping the intensity of the dc field the oscillating attraction of the ions to the magnetic poles effectively filters the ions of each independent "slug" based upon their mass. As the ion oscillatory motion increases, ions eventually impact the poles and are turned into neutral particles invisible to the ion collector. Therefore by knowing the energy level of the magnetic field the ion collector, the supporting circuitry is able determine a mass for each ion detected (Willard et al., 1988). The spectra detected by the ion collector for each individual "slug" is characteristic of an individual compound. The small charge created by the ions striking the detector are amplified and exported (Kuhn, 1992) to the computer. This spectra is analyzed by software and compared to a library of spectra to determine the identity of the unknown compound.

Storage of Organic Samples

Extracted samples should be stored in glass with ground glass stoppers (Jüttner, 1986). Glass vials with Teflon lined silicone septum caps are suggested (West et al., 1995) for use with auto-samplers. Since hydrocarbons photoreact, sample

vials should receive limited exposure to intense light (Jüttner, 1988; Helmig & Arey, 1992).

The samples must be refrigerated to about 4°C until analysis (Federal Register, 1995; McDonald & Wastney, 1995; Quigley & Corsi, 1995; Standley & Simoneit, 1990) and analyzed within 7 days (Federal Register, 1995).

Regulations

The 1990 amendments to Title V of the *Clean Air Act* (CAA) classified VOC as an important category of compounds to be regulated. Many of the anthropogenic VOCs were identified as HAPs or air toxics, substances which can cause serious health and environmental effects including; cancer, birth defects, nervous system disorders, and even death. The 1970 Clean Air Act gave the EPA the authority to list HAPs that need to be regulated and then to regulate their release. This 1970 list of HAPs was short and incomplete. The 1990 amendments greatly expanded this list to 189. Congress compiled this list on the basis of scientifically based potential hazard. The EPA is responsible to regulate the emissions of these 189 HAPs (U.S.EPA, 1993).

Additionally, many VOCs have been shown to be precursors to smog (a mixture of pollutants, such as ground-level ozone, produced by chemical reactions in the air) formation because they efficiently form ozone (O_3) in photosensitive reactions with oxides of nitrogen (NO_x) (Pandis et al., 1991). VOCs may also act as sources of odors, ozone and aerosol precursors (Ingram et al., 1995a) and some may be toxic to individuals that come into contact with them (Mihelcic et al., 1993).

Materials and Methods

Sample Selection and Handling

Green nominal two-inch by six-inch lumber was cut to create two 48-inch long pre-samples. Each piece of lumber was cut in half, then, measuring from the bisecting

cut, one 48-inch pre-sample was cut from each half. The pre-sample boards were randomly placed in one of two separate charges. This created two matched charges of twenty two-inch by six-inch by 48-inch pre-samples. Each charge of lumber was tightly wrapped in plastic (0.006 inch thick clear) and the seams were sealed with duct tape. The wrapped lumber was kept to a manageable weight and size by wrapping five boards to a bundle, four bundles per charge. Bundles were labeled with date, and the pile/charge it came from, in order to keep the randomization and matching intact. The eight bundles were placed into a freezer (-15 °C) until the kiln charges were run.

Kiln Configuration

The laboratory kiln at the Oregon State University Forest Research Laboratory was modified for this research (**Figure 2.1**). The vent stacks were sealed and many of the holes in the walls were sealed with silicone. The kiln accepted lumber 111.76 cm (44 inches) long. The maximum width of any charge could be 45 cm (17.75 inches) and the maximum height of 64-cm (25.25 inches).

A closed steam heating system was used to heat the kiln. Coils transferred the heat to the kiln. Steam was supplied by the house boiler. The charges of lumber were not artificially humidified by stream spray. This would have significantly affected all attempts at determining a water balance. The water that was introduced into the system by the wet-bulb was ignored because its volume was relatively small compared to that released from the lumber.

Experiment Start-up

Twenty-four hours before each laboratory kiln charge, four bundles representing a kiln charge were removed from the freezer and allowed to thaw for 20 hours. Packages remained sealed in plastic to help retain any volatiles. Two hours before the scheduled beginning of the kiln run, the support gases (**Figure 2.1-A**= Hydrogen, **B**= Propane, **C**= Nitrogen) were turned on. The J.U.M. model 3-200 total

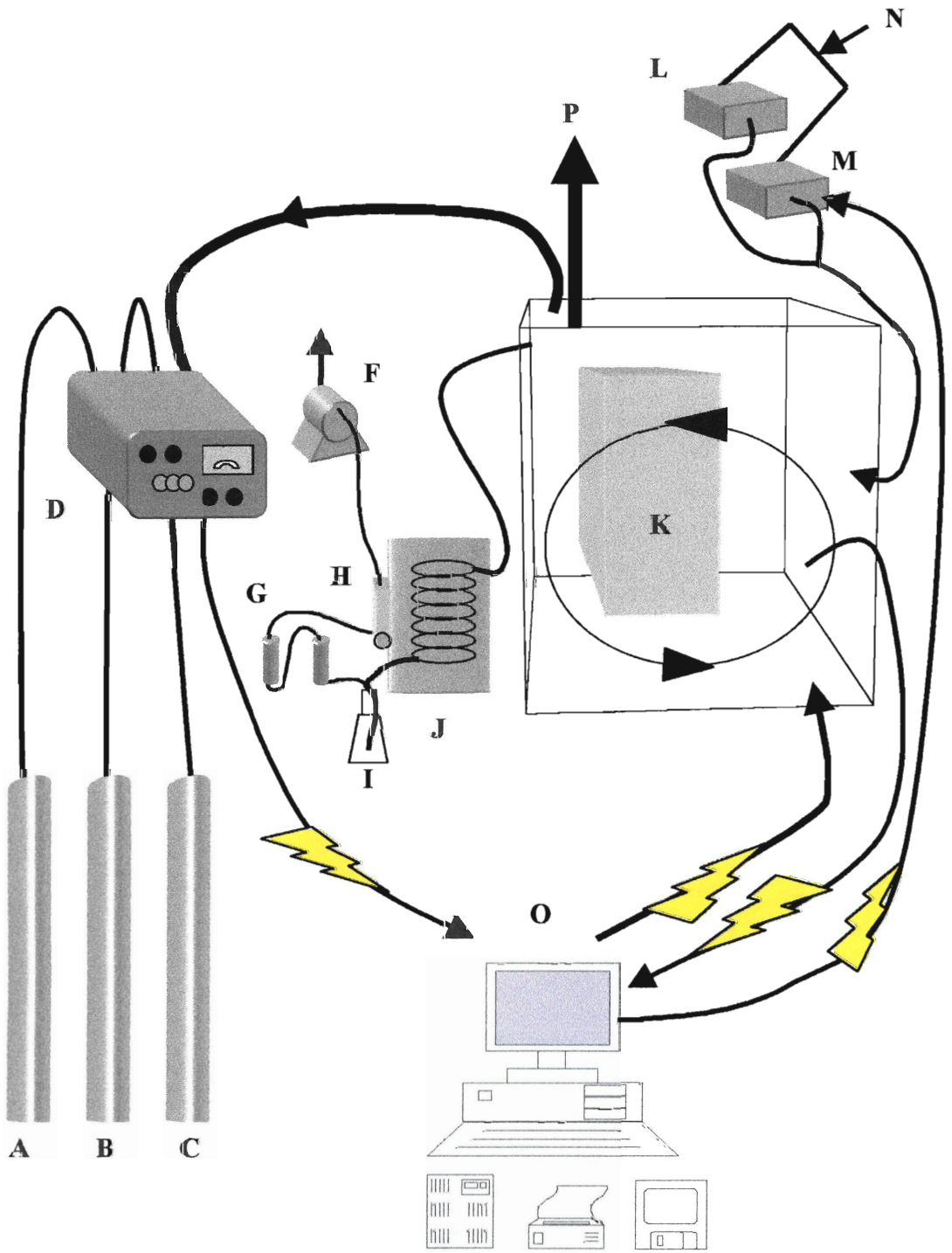


Figure 2.1 Laboratory kiln configuration. The charge of lumber (K) is inside the kiln which is controlled and monitored by the data acquisition/controller computer (O), D represents the total hydrocarbon analyzer (THA) and A,B,C are the support gases. The adsorption sampling train (F,G,H,I,J) was used to collect samples for speciated analysis and the kiln make-up air inlet is represented by L,M,N.

hydrocarbon analyzer (THA)(**D**) was turned on and allowed to warm to its set-point temperature (190 ºC) and the detector to stabilize.

Grade 5.0 Hydrogen at 20 psig was used for the ionization flame and the internal regulator of the THA metered the gas to the ionization chamber as needed. Grade 5.0 Nitrogen at 15 psig was used for the zero gas and purge gas. The nitrogen was metered into the ionization chamber to zero the system every few hours through out the experiment. Propane at 885 ppmv in air was specially mixed for this experiment. 885 ppmv was set on the span calibration when the propane flowed through the detector. The maximum adjustment required was less than three percent of the reading during the span adjustment which occurred every few hours.

Just prior to loading the kiln, the four bundles of 48-inch pre-samples were unwrapped and each pre-sample was trimmed to create a 44-inche sample by trimming two inches from each end. This was done so the boards would fit into the kiln and to obtain "fresh" ends, free from any end drying effects that may have occurred during storage. Each laboratory kiln charge was two boards wide with ten courses on 0.75-inch stickers (**K**).

Kiln Schedule

The computer program Control EG ™, measurement and control software developed by Quinn-Curtis, was started on the kiln controller computer (**O**) and the specific control files were loaded and initiated. This program controls the kiln, monitors and displays specified parameters in real time, and gives soft and hard output of selected information.

Laboratory kiln conditions were set to closely represent a typical commercial schedule (**Figure 2.2**). The dry-bulb original set point was room temperature with a ramp of 0.5 °C/minute (0.9 °F/minute) until the 82.2 °C (180 °F) set point was achieved. This dry-bulb temperature was held for the duration of the schedule. The wet bulb original set point was room temperature with a ramp of 0.5 °C/minute (0.9 °F/minute) until a set point of 76.7 °C (170 °F) was achieved. This wet-bulb

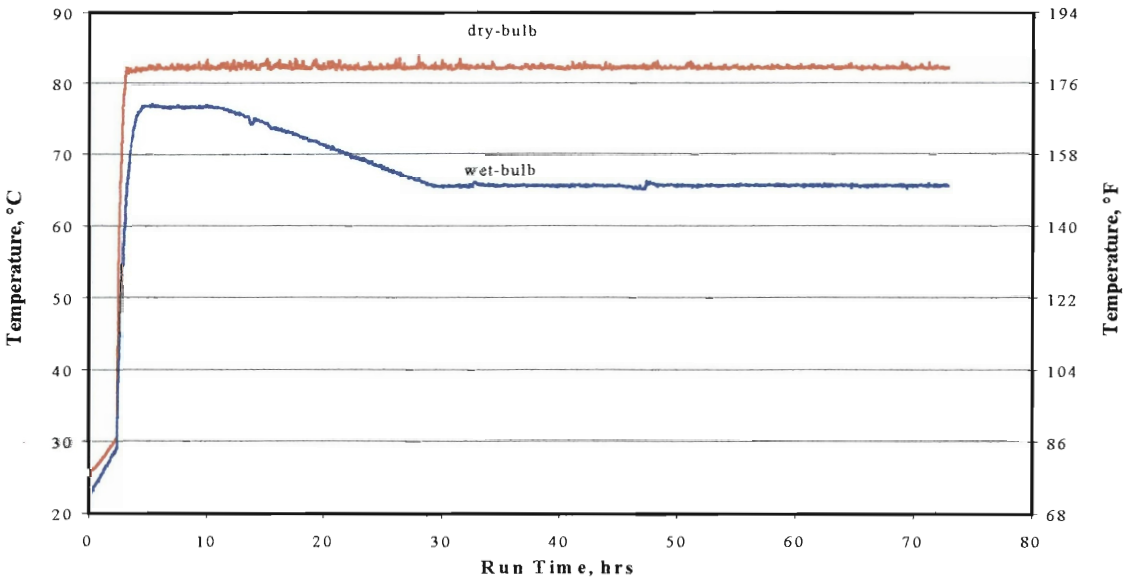


Figure 2.2 Kiln schedule with initial set-points of 82 °C and 76.6 °C. At the twelve hours the wet-bulb was ramped at -0.59 °C/hour to 67 °C, then held.

temperature was held until the 12-hour mark in the schedule, when it was ramped at -0.59 °C/hour (-1.1 °F/hour) to 66.7 °C (152 °F). This wet bulb temperature was held until the completion of the 72-hour schedule.

The laboratory kiln had compressed house air (**N**), of known composition, metered into it by an MKS Instruments, Inc. 0-50 liter/minute Type 0558A mass flow meter (**L**) and Type 1559A mass flow controller (**M**). This gave a slightly higher than ambient pressure in the kiln. Flow through the meter was manually controlled, as needed, with a needle valve. The mass flow controller modulated the flow based on a signal from the computer, increasing the flow, as more venting was required. This meter was set to maintain a minimum of 4.0 liters/minute flow, slightly more than that being drawn by the THA (3.0 liter/minute) and the adsorption sampling train (0.8 liter/minute).

Compound Collection

Samples were collected for compound identification and quantification by condensation of the less volatile/larger and water-soluble compounds and by

adsorption onto activated charcoal. A 0.8 liters/minute sample was drawn from the kiln through a chilled condenser (**J**), built by placing a Teflon® coil inside a plastic 3-gallon cooler. Ice water was added to the cooler to chill the gas to the dew point of water and therefore condense water and less volatile and water-soluble organics. Exhaust from the chiller at approximately 20 °C. The condensate was collected in a 250-ml Erlenmeyer flask (**I**). The dehumidified sample stream then passed through two glass Orbo™-32 activated charcoal tubes in series (**G**) (Supelco Inc. #2-067), which were replaced based on the THA reading to ensure the charcoal did not become saturated.

Each Orbo™ charcoal tube was labeled with an individual identification number in permanent marker. Tubes were installed as manufacturer's directions indicated, with the end containing the glass wool "plug" up stream. Flow was maintained at 0.8 liters/minute, well within the Orbo™-32 charcoals maximum suggested flow of one liter/minute. The pump used to pull exhaust through the adsorption sampling train was turned on as soon as the schedule started.

The activated charcoal tubes were replaced every 45 minutes during the first 12 hours, every hour for the next 12 hours, every three hours during the next 24 hours, and every six hours during the remainder of the schedule. As each tube was removed, its ends were capped which effectively isolated the charcoal in the glass tube and ensured, that no more organics were collected or lost during storage.

The equipment was monitored frequently and adjusted many times throughout each experiment. The temperature of the cooling water was monitored. The exhaust flow rate was monitored and adjusted at each sampling interval.

Lumber Physical Properties Analysis

All sample boards were weighed green, after kiln drying, and after oven drying. The physical properties of each board were measured after oven drying. Initial (green) moisture content and kiln dry moisture content were calculated based upon oven dry weights. The percentage of heartwood was calculated by averaging the

percentage of heartwood measured at each end of the board. The number of rings were counted at one end and the specific gravity was calculated by using dimensional measurements taken of oven dry samples. Each sample board had its thickness and width measured in two places with digital calipers.

Sample Storage

All of the labeled, capped charcoal tubes were placed in a single Ziplock™ plastic bag. This bag was placed in an ice-chilled cooler until organic extraction could be performed. Water samples were stored in an Erlenmeyer flask with ground glass mouth (Jüttner, 88) for a few days. The glass stopper was wrapped in Parafilm M® to ensure the stopper stayed in tight. Water samples were stored in an ice-chilled cooler until organic extraction could be performed.

Compound Identification

HPLC grade methylene chloride (dichloromethane - CH_2Cl_2) was used to extract (Ingram et al., 1995a; McDonald & Wastney, 1995) the volatiles from both the charcoal and water samples. Undecane, $C_{11}H_{24}$ (Fisher Catalogue # 14066-1000) used as an internal standard. A standard dichloromethane solution was prepared by pipetting one gram of undecane into a 1000-ml clean dry volumetric flask placed on a tared electronic balance. The flask was then filled to the 1000-ml mark with dichloromethane and stoppered. The flask was then inverted and "swirled", mixing the contents. The prepared standard solvent solution was then transferred to a 1000-ml brown glass solvent bottle.

Condensate

Two extractions with five mils of standard dichloromethane solvent solution were performed on the water sample from each kiln charge. Each water sample was vigorously shaken, then immediately 250 ml of the water sample was poured into a

clean separatory funnel. Five ml of standard dichloromethane solvent solution were added to the sample container, swirled to ensure that all surfaces of the storage container were "washed", then poured into the separatory funnel. The funnel cap was put into place, the funnel was inverted, and the valve was opened to relieve the pressure built up from the volatilization of dichloromethane. The valve was closed and the funnel and its contents were then vigorously shaken and swirled. The valve was periodically opened while the funnel was inverted, to relieve pressure build up from volatilization of dichloromethane. The funnel was placed upright in a ring stand, allowing the denser dichloromethane and extracted organics to settle to the bottom of the funnel.

To dislodge droplets of solvent that often clung to the walls of the separatory funnel, the contents of the funnel were swirled. The solvent/organic sample fraction was then carefully drained into a small glass Erlenmeyer flask. Five ml of the solvent was added to the funnel and the above process was repeated. The organic fraction was drained into the same small glass flask containing the first sample. The remaining water in the separatory funnel was discarded.

To confirm the extraction efficiency three samples were extracted four times. Each single extractant was analyzed separately. The results indicate that approximately 80% of the organics in the sample are extracted with each extraction confirming that at least 95% of the organics in the sample were extracted with two extractions.

Granules of anhydrous sodium sulfate (Na_2SO_4 - $7H_2O$) were placed in the bottom of the flask for about 10 minutes to remove water from the organic solvent and sample (Adams, 1991). The salt granules clumped, dissolved, and stuck to the glass while the extractant remained "wet", when the extractant was dry they moved freely. A two-ml sub-sample was then taken from the flask, while avoiding the sodium sulfate granules, and transferred into a labeled, crimp-seal, auto-sampler vial. The seal was crimped and the sample was stored at 4 °C (Federal Register, 1995; McDonald & Wastney, 1995; Quigley & Corsi, 1995; USATHAMA, 1990) in a dark environment. Samples were extracted, sealed in vials with Teflon™ lined caps and placed in the

freezer within three days of collection (Bayne et al., 1994; Federal Register, 1995; U.S. EPA, 1994). Analysis with GC-MS occurred within 21 days after sealing.

The glassware was rinsed between extractions with water, five mils of HPLC grade methanol and finally five mils standard dichloromethane solvent solution (Brown, 1971). Between rinsings the separatory funnel drained.

Activated Charcoal Tubes

The activated charcoal was removed from the glass tubes by breaking the end of the glass tube, with pliers, such that a larger diameter opening was obtained. The foam rubber plugs in the tubes were removed with a dissecting probe that had the tip bent by simply tapping it on a hard surface; a small bur was all that was required to hook the plugs. The charcoal was poured into correspondingly-labeled a two ml plastic Corning® Cryogenic screw top vial (Corning #430488, 25704-2). Series pairs of charcoal tubes were combined into one vial for analysis.

When 15 vials of charcoal (15 series pairs) were prepared in the manner described above, 1 ml of the standard dichloromethane solvent solution was pipetted into each plastic vial with a Nichiryo repeater pipette set to position 1, with a 60 ml tip.

These 15 vials were sealed with screw caps and placed into a small beaker such that the sample vials remained upright. Water was added to the beaker to a level even with the upper surface of charcoal/solvent. The beaker was then placed in an unheated sonicator bath, for 15 minutes, with water level higher than that in the beaker but several centimeters below the rim of the beaker.

After sonication, the liquid fraction was removed from the vials using a 10-ml glass Micro-Mate® syringe with a 16-gauge metal Luer-lock tip (Popper & Sons, Inc.). The non-sterile Millex-FG_{13} 0.2-µm filter ensured that the resulting liquid sample was free of particulate material, necessary for gas chromatographic analysis. The needle used to reach the bottom of the vial was a 16-gauge Luer-lock needle with the sharp point snipped off, creating a dull tip. The needle tip was placed into the sample fluid

and the plunger of the syringe was pulled drawing solvent through the filter into the syringe barrel. When all the free solvent/extracted volatiles were removed from the charcoal, the filter and needle were disconnected from the syringe and the contents collected in the barrel were transferred to a correspondingly labeled two ml wide mouth, amber, crimp-seal glass auto-sampler vial (Supelco Inc. # 2-7066). Typically, less than one ml of solvent/sample was collected because some solvent remained wetting the charcoal. The vials were kept in a rack so they did not tip over. The 11 mm crimp-seal cap (Supelco Inc. # 2-7360), with red Teflon®-faced silicone septa, were set upon the vial but not crimped at this point. One ml of dichloromethane/undecane standard solution was then pipetted into the plastic vial containing the charcoal and it was sealed again.

The procedures above were repeated on each of the 15 sample vials. The liquid fraction of the sample was removed and transferred to its corresponding un-crimped crimp seal auto-sampler vial. This aliquot of solvent/internal standard and extracted organic sample effectively filled each vial. The Teflon®-lined silicone crimp seals were then crimped with a crimping tool, sealing each vial. The samples were stored below 4 °C (Federal Register, 1995; McDonald & Wastney, 1995; Quigley & Corsi, 1995; USATHAMA, 1990) in a dark environment. Samples were extracted, sealed in vials with Teflon™ lined caps and placed in the freezer within three days of collection (Bayne et al., 1994; Federal Register, 1995; U.S. EPA, 1994). Analysis with GC-MS occurred within 21 days after sealing.

The glass was cleaned between runs with the dichloromethane/undecane organic solvent and methanol (Brown, 1971). The filter was then discarded and the syringe barrel and needle were rinsed with the dichloromethane/undecane solvent used in the extraction. This was accomplished by filling the barrel with approximately two ml of the solvent, inverting the syringe (tip up), drawing approximately two ml of air, connecting the needle to the glass syringe barrel, turning the syringe/needle needle down, and expelling the solvent and air through the needle. Air was then drawn into the syringe and expelled three times to dry the barrel.

GC-MS Analysis

This study incorporated a Hewlett Packard 7673 GC auto-sampler injector manipulating a Hamilton 10 µL #80377 syringe (Hamilton Co., Reno Nevada). Two µL of sample were drawn from each sample vial and injected through a septa, into the injector port of a Hewlett Packard 5890 Series II Gas Chromatograph. The split/splitless injector port, set to a split ratio of 1:20, was controlled to a temperature of 200 °C (392 °F).

To limit contamination of the syringe barrel, it was thoroughly flushed between sample injections. A sample wash of 10 µL was drawn and expelled into the "waste" vial. The syringe was then inserted into the sample vial and the syringe plunger was drawn and expelled four times. The two µL sample was drawn and injected into the injector port as described above. The syringe was then washed two times with methanol (MeOH) by drawing the plunger up and then expelling the contents drawn into a waste vial. After two washes in MeOH, the syringe was washed two times in dichloromethane (CH_2Cl_2) in the same manner as described above.

To avoid the potentially large solvent tail, the injection port was vented to the atmosphere 30 seconds after initial injection, at this time the majority of the solvent and essentially all the sample had entered the column. The carrier gas was Grade 4.7 Helium carrier gas set to a flow rate of 1.02 ml/minute into the 60 meter Supelco 10 column (0.2 mm ID, phase film 0.2 µm, Catalog # 2-4170 Supelco Bellefonte, PA, USA). The GC oven was programmed to hold at 70 °C for two minutes, ramp at six °C/minute to 210 °C, then hold for 18 minutes. The separated unknown VOC components moved to a Hewlett Packard 5971 quadrupole mass selective detector (mass spectrophotometer) set to an ionization energy of 70 eV, an accelerating voltage of 3.5 kV, a cathode current of 25 µA (Isidorov). The transfer line and ion source temperatures were set to 280 °C and 180 °C respectively. Identification of the individual components of the samples were determined by retention time and comparison of mass spectra with the NIST/EPA/MSDC 54K Mass Spectral Library and Hewlett Packard MS Chemstation (Catalog #HP G1030A).

Both internal and external standards were used to confirm compound identification and to quantify results. The detector sensitivity to each compound was determined by running a mixture of knowns, making possible accurate quantification of the unknowns. The external standards were known concentrations of individual anticipated monoterpenes, and a known mixture of these monoterpenes.

Calculations

The calculation procedure used to determine the dry gas flow rate, moisture content of the wood, hydrocarbon emissions, and monoterpene emissions from the kiln is schematically represented in **Figure 2.3**. The flow calculations were used to determine the total emissions determined by the adsorption sampling train and the THA. The emissions rate times the length of the time interval yields emissions for that interval. Summing these from the beginning of the drying schedule to any target lumber moisture content or time yields the total emission to that point. 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 as measured by weight change.

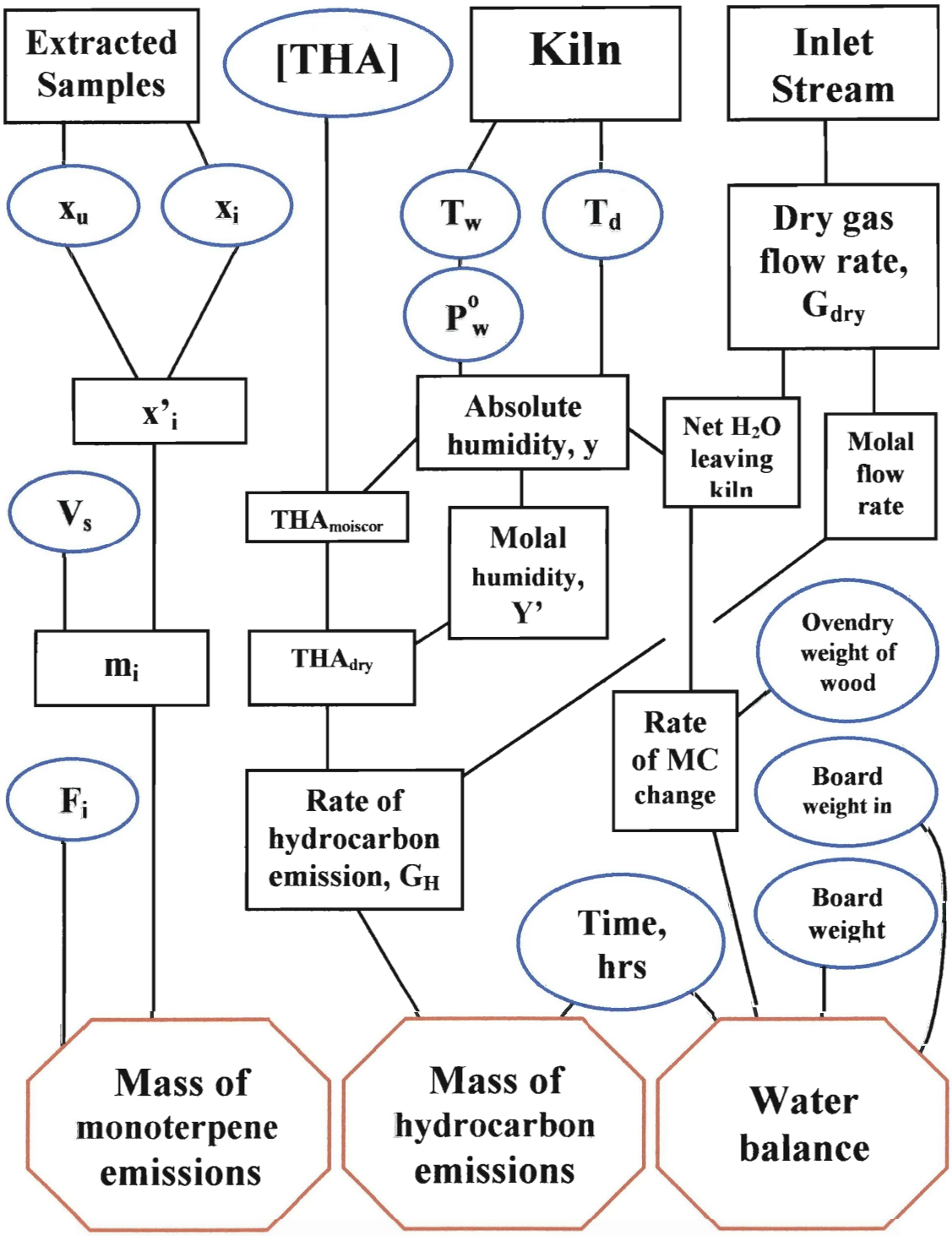


Figure 2.3 Calculation procedure. Measured variables are in ovular shaped fields, calculations and collected samples are in rectangular fields, and the results are in the octagonal fields.

Absolute Humidity

Vapor pressures were calculated for the exhaust stream (Yaws, 1977)

$$P_w^0 = \left(\frac{101325\ \text{Pa}}{760\ \text{mmHg}}\right) 10^{16.373 - \frac{2818.6}{T+273.16} - 1.6908 \log(T+273.16) - 0.0057546*(T+273.16) + 4.0073*10^{-6}*(T+273.16)^2} \quad (1)$$

where, T is the wet-bulb temperature (°C) inside the kiln. The absolute humidity inside the kiln was calculated as

$$y = \frac{MW_{water}}{MW_{air}} \frac{1}{\frac{p}{\frac{\Psi_C}{100} * p_w^0} - 1} - \left((T_{DB} - T_{WB}) \left(\frac{h_g / k_y}{\lambda} \right) \right) \quad (2)$$

where p=101,325 Pa, Ψ_C=100%, h_g/k_y=0.95kJ/(kg-K), and λ=2419.3kJ/kg. The molal humidity inside the kiln was calculated as:

$$Y' = \frac{MW_{air}}{MW_{water}} * y \quad (3)$$

Dry Gas Flow Rate

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 removal rate was calculated as:

$$G_{H_2O} = G * y * \left(\frac{1000g}{1kg}\right) \quad (4)$$

Water Balance

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

$$X_n = X_o - 100 * \frac{\sum_{j=1}^{j=n} G_j * y_j * \Delta t_j}{m_{OD}} \quad (5)$$

Total Hydrocarbon Analysis

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

$$THA_{moiscor} = \left[\frac{THA}{(1 - A)^{E * y + A}} \right] \quad (6)$$

where A = 0.79 and E = -6.649. These were determined in a separate experiment in which known concentrations of moisture and hydrocarbon were measured by the detector. Moisture in the 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:

$$THA_{dry} = THA_{moiscor} * (1 + Y') \quad (7)$$

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

$$G_H = (G') \left(\frac{THA_{dry}}{1{,}000{,}000} \right) (MW_{propane}) \left(\frac{1{,}000g}{1kg} \right) \quad (8)$$

The total mass of emissions at 12% moisture content was determined by:

$$m_H = \sum_{j=1}^{n} G_{H_j} * \Delta t_j \quad (9)$$

where n corresponds to the interval at which the wood moisture content is 12% as determined by equation 5.

Adsorption Sampling Train

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

$$X'_i = \frac{1{,}000 \frac{g}{\ell}}{x_u} * x_i \tag{10}$$

where i represents the i^{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,

$$m_i = X'_i * V_s \tag{11}$$

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

$$M_i = \sum_{j=1}^{n} \left(\frac{G'_j}{G'_{CH_j}} \right) * (m_i)_j \tag{12}$$

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

Specific Gravity

The specific gravity (SG) of the laboratory samples was calculated

$$SG = \frac{m_{OD}}{L * W * D * \rho_{H_2O}} \tag{13}$$

where m_{OD} is the weight of the oven dry wood (g), ρ_{H_2O} is the density of water, and length (L), width (W), and thickness (D) are in meters.

Results and Discussion

Wood Properties

Analysis of wood characteristics for the two charges of lumber (**Table 2.1**) shows that both charges had about 80% heartwood. The average number of rings was 5.7 rings per inch and the oven dry specific gravities were 0.47 and 0.45. Coastal Douglas-fir is reported as having a specific gravity of 0.48 (Haygreen & Bowyer, 1989). The initial moisture contents were 64.2 and 64.7 % and the final moisture contents were 8.33 and 9.03 % on an oven dry basis. For all intents and purposes these two charges were matched.

Table 2.1 Wood properties.

Charge ID	Green MC %	Heart %	Rings $^{\#}/_{inch}$	Specific Gravity	g Monoterpene kg_{ODwood} @ 12 % MC	g THC kg_{ODwood} @ 12 % MC
A	64.15	78.9	5.9	0.47	0.22	1.04
B	64.66	81.6	5.5	0.45	0.22	0.96

Emissions Based upon Total Hydrocarbon Analyser

The hydrocarbon concentration in the exhaust air increased rapidly from near zero to 3513 ppmv at approximately six hours into the schedule when venting began (**Figure 2.4**). The hydrocarbon concentration in the kiln likely increased over this six-hour time interval due to the kiln not venting. After venting began at the six-hour point in the schedule, the hydrocarbon concentration rapidly decreased. Simultaneously the venting rate increased (**Figure 2.5**), resulting in an emissions rate

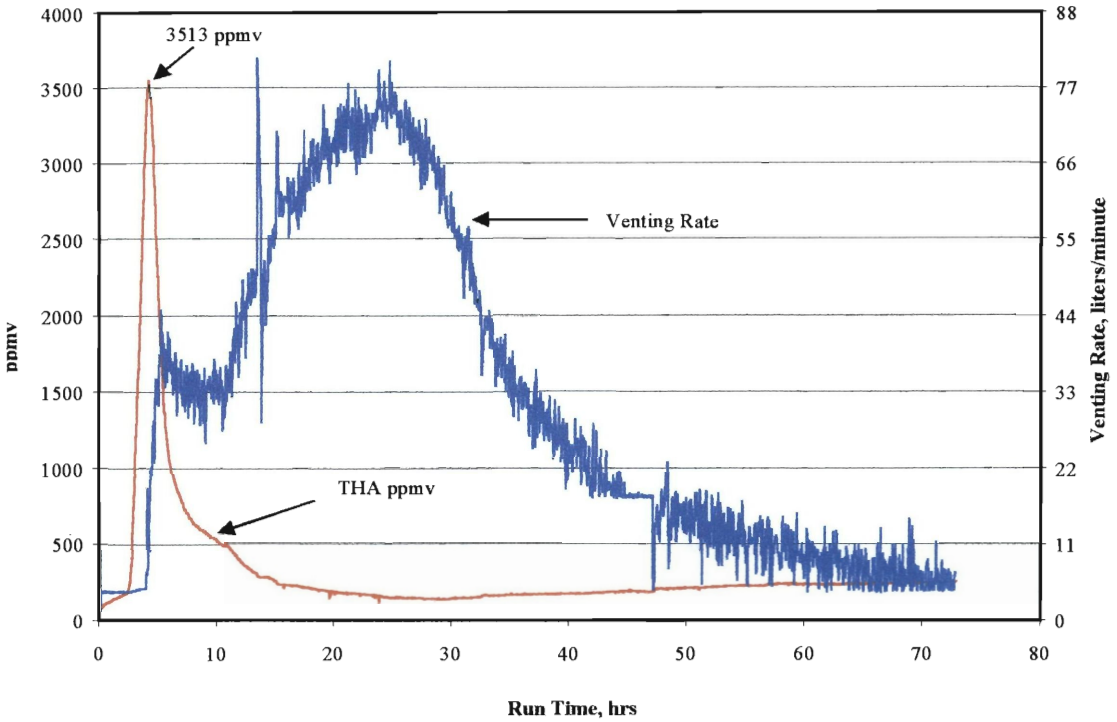


Figure 2.4 Laboratory kiln emissions and venting rate. 2x6 Douglas-fir emissions, measured with a THA, on a dry gas basis and reported in parts per million volumetric basis compared to the venting rate, liters/minute.

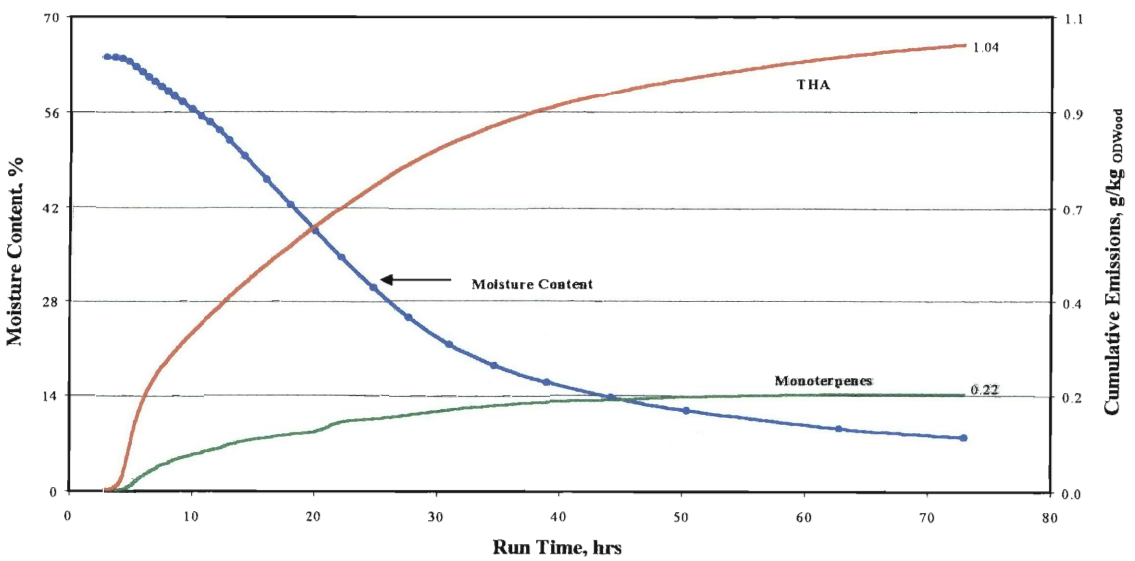


Figure 2.5 Cumulative emissions and charge moisture content. Laboratory kiln charge A of 2x6 Douglas-fir dried to 12% moisture content and the moisture content of the charge.

that was initially high as the accumulated hydrocarbons were vented. After hour eight in the schedule the emissions rate decreased for the remainder of the drying schedule.

The total quantity of hydrocarbon emissions from charge A was 1.04 g/kg_{ODwood} and for B the total was 0.96 g/kg_{ODwood}. It is not know if the difference is due to actual variability of the VOCs released or sampling error. The average of these two quantities (1.0 g/kg_{ODwood}) is 2.25 times the value reported for Douglas-fir heartwood by NCASI (1996) (0.43 g/kg_{ODwood}) and 6.9 times the value they reported for emissions from sapwood (0.14 g/kg_{ODwood}). Wu (1997) reported 0.99 g/kg_{ODwood} for coastal Douglas-fir dried in a laboratory kiln using a similar schedule.

Between hours 8 and 30, as the moisture content of the wood decreased rapidly and the cumulative emission increased rapidly (**Figure 2.5**). 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 the moisture content of the charge. When cumulative emissions are plotted as a function of moisture content (**Figure 2.6**) it is clear that the quantity of emissions released was nearly proportional to the change in moisture content from when the charges moisture content is approximately 53% to the end of the schedule. Even though many of the volatile compounds released from Douglas-fir as it dries are not soluble in water, it is possible that they may move to the surface of the drying lumber 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.

Emissions Based on the Adsorption Sampling Train

GC-MS analysis of monoterpenes desorbed from activated charcoal traps and extracted from the condensate trap indicates that α-pinene is the dominantly emitted monoterpene (**Figure 2.7**). α-pinene is expected to be the most abundant species

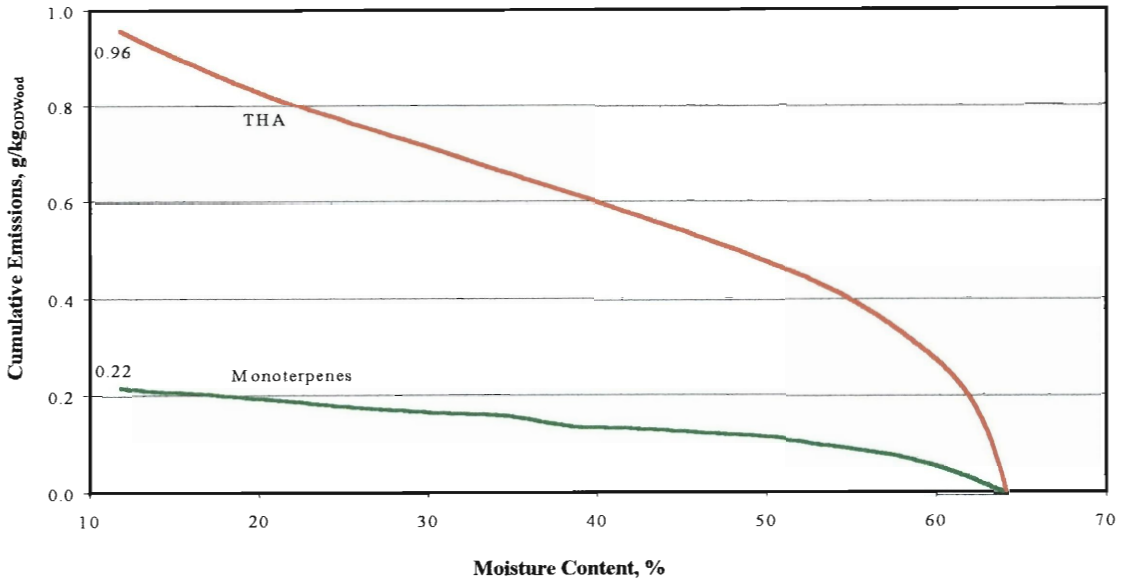


Figure 2.6 Cumulative emissions vs. moisture content. 2x6 Douglas-fir dried to 12 % moisture content.

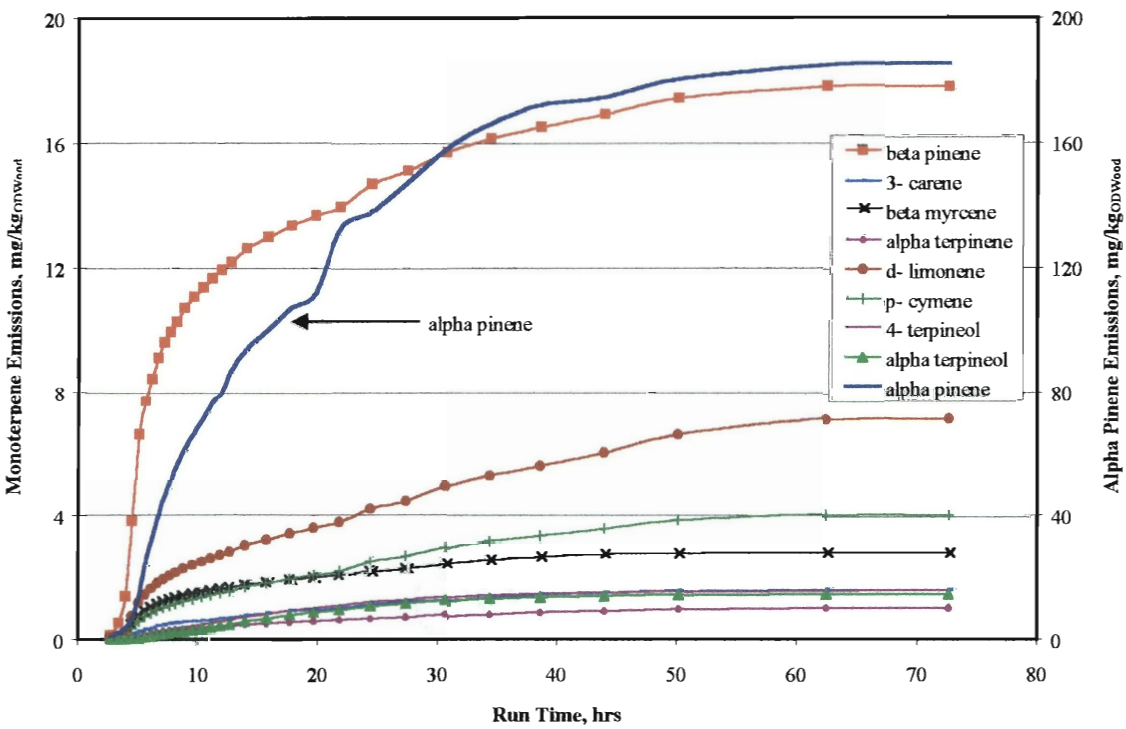


Figure 2.7 Cumulative speciated monoterpene emissions. Laboratory charge A, 2x6 Douglas-fir, dried to 12% moisture content.

because it is a present in relatively high concentrations in conifers. 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 ratios of monoterpenes detected in the veneer drier exhaust is similar to that observed for the lumber dry kiln, with α-pinene being detected in concentrations several times greater than the others. Initially there was a high rate of monoterpene emissions but as the schedule continued the rate deceased. This trend mirrors the trend seen for THC as measured by the THA. The total quantity of monoterpenes measured for each charge was similar, 0.22 g/kg_{ODwood}.

α-pinene was the monoterpene collected in the highest quantities from Douglas-fir. β-pinene and d-limonene were the next most abundant monoterpenes identified. The contribution of individual monoterpenes to the total detected emissions of a veneer drier, drying Douglas-fir (red fir), were found to be predominantly α-pinene, 54.8 %, while β-pinene and limonene made up 6.8 % and 5.3 % respectively (Cronn et al., 1983). In that study, α-pinene emissions were approximately eight times those of β-pinene. In the present study total α-pinene emissions were ten times greater than those measured for β-pinene.

Comparison

The total hydrocarbon quantity reported by the condensation/adsorption method was 22% of that reported by the method using the THA. The total VOC accounted for by the adsorption sampling train was 0.22 g/kg_{ODwood} where as the THA detected an average of 1.0 g/kg_{ODwood} for nominal 2"x6" Douglas-fir lumber. The most obvious reason for this difference is that the condensation/adsorption method measure monoterpenes compared to the THA method, which measures most organic emissions.

Uncollected Monoterpenes

It has been noted that less than half the organics measured in wood prior to lumber drying are collected and measured in the exhaust from a lumber dry kiln (Ingram et al., 1995a). One source of undetected organics could be volatile compounds passing through the condenser and the charcoal without being either condensed or adsorbed. A slight scent of "wood" after the adsorption sampling train pointed to this as a valid hypothesis. However, when the first and second charcoal tubes were analyzed separately (**Table 2.2**) one can see that nearly all the organics detected by the GC-MS are collected in the first tube. It is, therefore, highly unlikely that a significant amount of these compounds are in the gas leaving the sampling train.

Table 2.2 Charcoal adsorption efficiency. The first charcoal tube in the series collected many times more monoterpenes than the second charcoal in the series. This indicates that the second charcoal tube was not saturated.

Charcoal Order	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
	α-pinene	β-pinene	Δ-3-carene	β-myrcene	α-terpinene	d-limonene	p-cymene	4-terpineol	α-terpineol
1	6581.5	134.0	35.1	59.9	40.7	303.5	110.2	3.0	3.8
2	28.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

To verify this, additional tubes could have be placed in the series. However, if compounds were not adsorbed onto the charcoal in the first two tubes, it is unlikely that they would be adsorbed by additional tubes. A better verification method would be to sample the gas leaving the adsorption sampling train using the total hydrocarbon analyzer. This would detect monoterpenes as well as most other organic compounds passing through the sampling train. A significant concentration of organics detected by the analyzer would mean that non-monoterpene organic compounds are passing through the sampling train.

Extraction Efficiency

Another possible explanation for the differing results from the two collection methods could be the extraction efficiency from the charcoal or losses of compounds during handling. However, multiple extractions established that each extraction removes 80% of the detected organics. Two extractions should, therefore, remove over 95% of the detected organic compounds. No attempt was made to determine if non-monoterpene compounds remained on the charcoal. Low molecular weight compounds could have been lost in sample handling; these would have likely been hidden in the solvent peak of the GC and not detected anyway.

Other Sources of Monoterpene Loss

A potential source of error in the absorption sampling train was the flow regulation, a simple ball flow regulator was used. This regulator continually needed adjustment and thus the flow rate reported was an average of flows observed. This source of error could only account for a small percentage of the difference between the two methods because the flow was adjusted every few hours. In the future a more accurate regulator with the ability to report flow rates to a data logger would be a significant improvement.

Storage of the extracted samples may also be a source for sample loss. Samples were extracted and frozen within a three days but the GC-MS analysis took up to 21 days to complete. Compound isomerization and loss may have occurred during storage. It is alsolikely that many additional compounds were present in the extracted samples concentrations below the threshold of the reports generated. Likewise, there may have been components in the emissions, such as formaldehyde, methanol, and acetic acid, which were not tested for and thus could account for some of the discrepancy between the two methods. It is unlikely that any one or a combination of several of these sources of sample loss or undetection could account

for the five times lower total emissions detection. It is more likely that compounds not analyzed for account for the difference.

Conclusions

Adsorption and condensation of monoterpenes was successfully conducted on the humid venting exhaust from a lumber dry kiln. The method employed to collect samples for speciated analysis does not account for all the volatile compounds in the exhaust from a lumber dry kiln drying Douglas-fir. Total hydrocarbon analysis, using an FID, reported five times more volatiles in the exhaust. Condensation and adsorption of volatiles with subsequent organic extraction appears to produce samples representative of the total hydrocarbon emissions in that the shapes of the total hydrocarbon emission curves are similar. Even though the total emissions detected were less for the condensation/adsorption method, the speciated exhaust profiles may be able to be scaled up to represent an entire kilns emissions.

Further research is needed in the area of comparing the emissions detected by condensation and adsorption design and a THA to more accurately determine their relationship. Studies into the other components on the emissions from kilns may give new insights into the true relationship between the THC detected from adsorption and the use of a THA.

CHAPTER III VOC Emissions from Douglas-fir Comparing a Commercial and a Laboratory Kiln

Abstract

The 1990 Amendments to Title V of the Clean Air and Clean Water act are forcing emitters of volatile organic compounds to obtain operating permits based upon the quantity and species of emissions produced. Operators of lumber dry kilns are subject to Title V permitting due to the volatile organic compounds emitted from lumber as it dries. This research project compared a commercial lumber dry kiln with a laboratory lumber dry kiln. The results showed that when drying matched charges of 2x6 inch Douglas-fir the commercial kiln emitted 1.07 g/kg_{ODwood} (2.05 lbs/mbf) while the laboratory kiln emitted an average of 0.99 g/kg_{ODwood}. This indicates that the laboratory kiln, running the same drying schedule, may be a representative model of a commercial scale lumber dry kiln. The use of this laboratory model is much more efficient for monitoring emissions because of its location, size of lumber charge, and proximity to laboratory analysis equipment. The small size of the lumber charge makes it possible to economically test various schedules quickly and to compare emission rates[2].

[2] The author wishes to acknowledge Frank Lumber of Mill City OR. and M-Sprague in Hillsboro, OR. for assistance on the project. This work was funded by USDA Competitive Grant 95-37500-2302.

Introduction

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 vocally 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 these processes. Regulations and public attention are forcing the industry to address the issue of volatile organic compound (VOC) emissions by installing costly emission control technologies on some processes.

The lumber industry has great interest in the amount of hydrocarbon being emitted from their drying process because of the expense of EPA Title V permitting issues. The Clean Air Act (CAA) states that it is necessary to describe dry kiln emissions, such that potential Hazardous Air Pollutants (HAP) sources as well as benign VOC sources are identified. HAPs are chemicals that cause serious health and environmental effects including; cancer, birth defects, nervous system disorders, and even death.

The desire for clean processes as well as the fear of noncompliance are forcing kiln operators to obtain Title V permits based upon quantities of emissions that are potentially greater than they actually produce. Until recently (Ingram et al., 1995a; NCASI, 1996; Wu, 1997), commercial kiln operators had little to no scientific knowledge of the quantity of emission being released from lumber dry kilns as the charge of lumber was dried to target moisture content. In fact there are no published studies detailing the emission quantity from commercial kilns. This study directly addressed this data void by monitoring the emissions from a commercial kiln.

Increasingly, states are asking for speciated VOC information in addition to total hydrocarbon measurements. There are no published studies describing the emission spectra expected in the exhaust. It is believed that a major component of the emissions released during lumber drying are VOC, hydrocarbons. Monoterpenes ($C_{10}H_{16}$) are expected to comprise a large percentage of the total hydrocarbon (THC) emissions. Monoterpenes are those substances our noses identify as the smell of wood. The major monoterpenes (α-pinene, d-limonene, and β-pinene) are expected to be emitted from a kiln during the peak drying rate of the kiln schedule (McDonald & Wastney, 1995; Wu, 1997), i.e. during the initial part of the schedule (Ingram et al., 1995a; Wu, 1997).

Monitoring a commercial kiln is time consuming, logistically difficult, and thus expensive. This study addressed the issue of kiln drying capacity and expected emission rates. The emissions from a commercial kiln and those from a laboratory kiln were compared using the same equipment and methods.

By developing a strong understanding of the emissions pattern and the relationship between Oregon State University's laboratory kiln, a great service will be done for the industry. The laboratory kiln's small scale and highly controlled environment are ideally suited to test a diverse species set and drying schedule library efficiently and economically.

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

Literature Review

Kilns emit many different VOC 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, since the chemical composition varies among species.

The species of emissions are likely to be condensation polymers of isoprene. These compounds are predominately monoterpenes ($C_{10}H_{16}$) of different configurations such as α-pinene, β-pinene, limonene, camphene, and myrcene (Cronn et al., 1983; Ingram et al. 1995a; McDonald & Wastney, 1995). These monoterpenes have boiling points of approximately 155 °C 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.

Emissions from lumber dry kilns are difficult to quantify because of their design. Often there are multiple sites of venting and many avenues for fugitive gas to escape detection, such as around the door seals. Most kilns have modulated control and no sufficient length of straight duct to conduct velocity profile measurements. No data was found in the open literature reporting emissions from lumber dried in commercial scale kilns. There were several studies published focusing on emissions from lumber dried in laboratory scale kilns. Sampling the exhaust stream of a charge of southern pine dried at 82.2 °C (180 °F) and 118.3 °C (245 °F), with a flame ionization detector (FID), Ingram et al. (1995b) reported emissions of 2.75 g/kg_{ODwood}. Chemical analysis of condensed volatiles from radiata pine dried at 120 °C (248 °F) and 140 °C (284 °F) revealed 0.23 and 0.32 g/kg_{ODwood} 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_{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, 0.99 g/kg_{ODwood} for sugar pine, 1.0 g/kg_{ODwood} for ponderosa pine, 1.29 g/kg_{ODwood} for western white pine, and 1.02 g/kg_{ODwood} and 1.53 g/kg_{ODwood} 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_{ODwood} of emissions were released from southern pine as it is dried. The limited literature on condensing volatiles suggests that a FID may indicate higher emission rates than those determined by condensing, with the FID results being closer to the actual emission rates. This may be due to more complete detection with the FID.

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. As the packages of lumber emerged from the sticker stacker, each was labeled with a "T" to denote that it was involved in a test and one-third of the package from charge one and two were given a number and then 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 row of packages. The overall length of the kiln charge was 64 feet.

Laboratory Charges

The lumber sampled for drying 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 12 20-foot, 8 14-foot, and 8 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 systematically randomized into four piles (**Figure 3.1**). There were two sets of matched charges created for each corresponding commercial kiln charge. The 48-inch lumber was tightly wrapped in plastic (0.006 inch thick clear) and the seams were sealed with duct tape. The wrapped lumber was kept to a manageable weight and size by wrapping five boards to a bundle, so there were four bundles for a lab kiln charge. Each bundle was labeled with date and lab charge identification number. The 16 bundles were then transported to the Forest Research Laboratory at Oregon State University and placed into a freezer (-15 °C) until the laboratory kiln charges were run.

Commercial Kiln

Kiln Configuration

The commercial kiln was a 64-foot single track (**Figure 3.2**) with a heat exchanger (**Q in Figure 3.2**) located on a catwalk above the loading doors. The test section of duct (**R**) was inserted in to the exhaust line prior to the heat exchanger (**Q**). The sample section of duct work consisted of a series of fins (**T**) which straightened the exhaust flow (**L** and **M**) and had a series of sealable sampling ports (**S**) at 60° intervals. Exhaust gas (**P**) left the heat exchanger and was replaced with ambient air (**N**). The sampling equipment for chemical analysis consisted of an ice chilled condenser (**J**), a water trap (**I**), two activated charcoal tubes (**G**), a flow meter (**H**) and

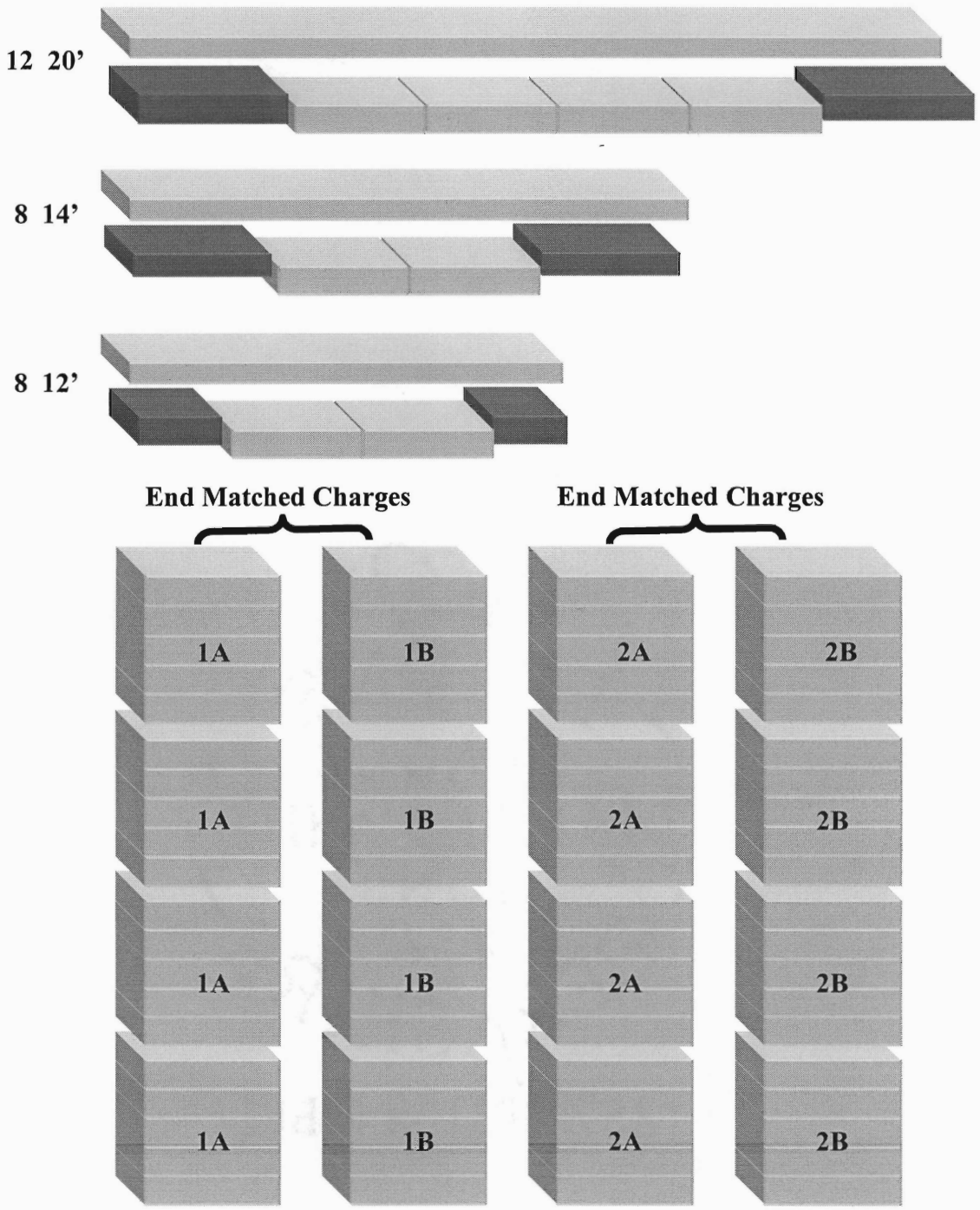


Figure 3.1 Lumber sampling, 2x6 Douglas fir. 12-20', 8-14', and 8-12' Douglas-fir 2x6's were sawn into 48" sample boards as detailed. The four sample boards from each 20-foot board were place one in each of the piles. The two sample boards from each 12- and 14- foot board were placed in one of the match charges, one board in each pile.

a small pump (**F**). Sample exhaust was supplied to the THA through a 15-foot heated sampling line (**E**).

The THA (**D**) was situated in a protective wood box and fastened to the decking of the catwalk, approximately 22 feet off the ground, near the heat exchanger. The support gas cylinders (**A**= Hydrogen, **B**= Propane, **C**= Nitrogen) were secured to a beam under the catwalk on ground level and Teflon tubing supplied the gasses to the THA.

Temperature and Relative Humidity Sensors

A relative humidity sensor and thermocouple were placed under the eave of the control building. The solid state sensor was wired direct to the monitoring computer for data acquisition. It was located under the eave in order to protect if from the elements but to keep it 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

The variable frequency drive (VFD) controlling the blower motor in the heat exchanger (**Q**) was controlled by a 3-15 psig air pressure signal from the kiln controller. The VFD had a remote output signal of 0-5 volts, which was proportional to the blower rpm. This signal was monitored and recorded by the data acquisition system. 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 0-5V signal and the flow through the heat exchanger. This relationship was used to determine the venting rate during the test charges.

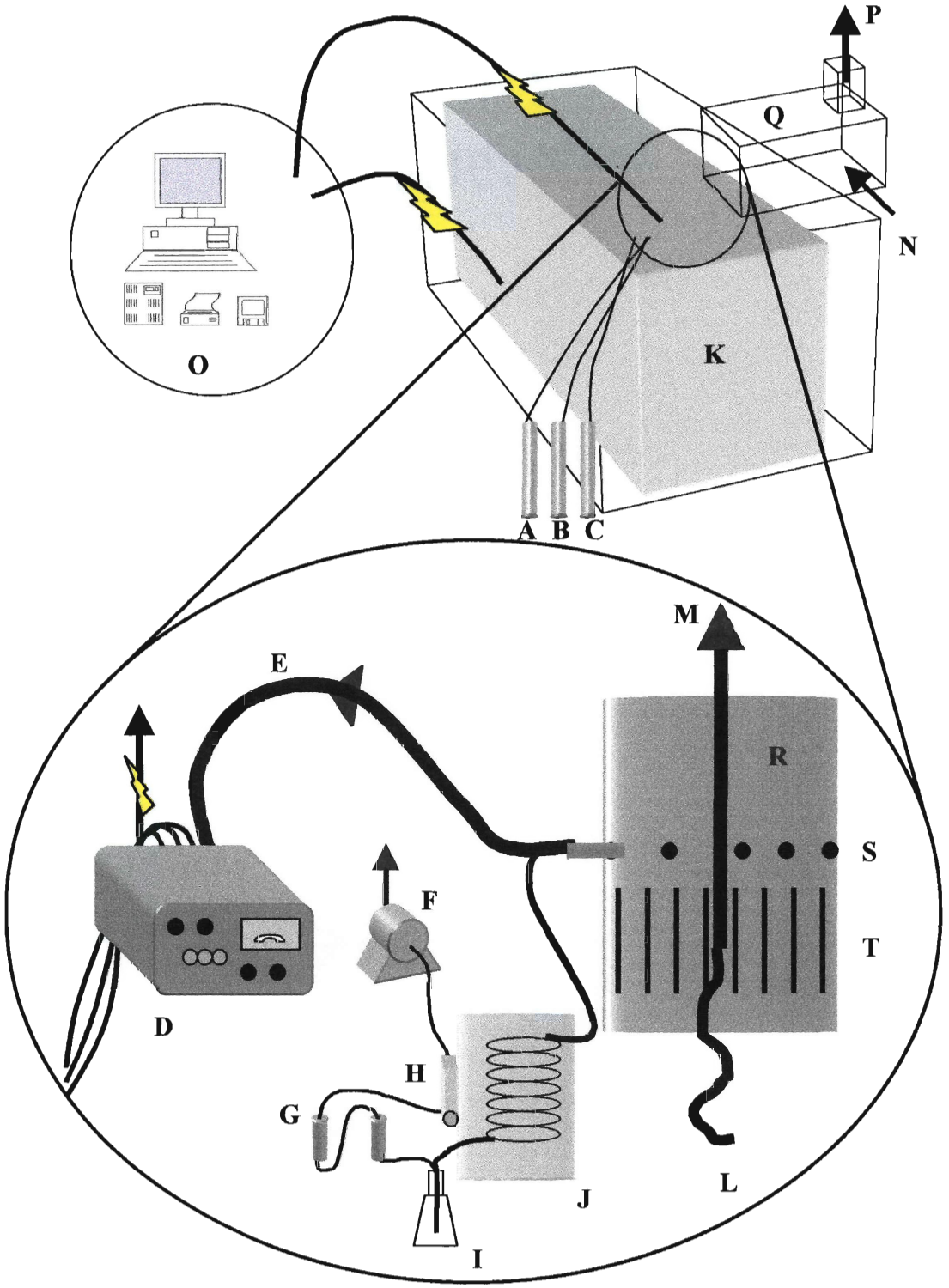


Figure 3.2 Commercial kiln configuration, Douglas-fir. The package of lumber (K) inside the kiln, the heat exchanger (Q), the data acquisition computer (O), the total hydrocarbon analyzer (D) and its support gases (A,B,C), the adsorption sampling train (F,G,H,I,J) and the vertical test section of duct (R).

Sampling Modifications

A 12-inch section of 12-inch diameter vertical duct (**R**), between the kiln and the heat exchanger was removed and replaced with a section containing a flow straightener (**T**), pitot sampling ports (**S**) around the circumference and a fixed three-holed rake type sampling probe. The flow straightener was a series of metal plates, parallel to the exhaust flow direction, welded in a web pattern. This pattern gave a uniform velocity profile across the diameter of duct and enabled flow measurements of the exhaust using a pitot tube. Sealable entry ports (**S**) were located every 60 degrees around the circumference of the duct to afford access to the exhaust stream for the pitot tube. The pitot tube was left in place during the test and data collected as a back-up procedure to the motor rpm for measuring the exhaust gas flow rate. The fixed sampling probe was a stainless steel tube with three $^{1}/_{16}$ inch diameter holes drilled on one side of the tube, at the center and 16.7% of the diameter of the stack from each end. They faced into the flow of the exhaust. This sampling probe was located after the flow straighteners.

Start-up Procedures

Two hours before the scheduled beginning of the laboratory kiln run the J.U.M. model 3-200 THA (**D**) was turned on and allowed to warm to its set-point temperature and the detector to stabilize. Ice water was added to the mobile condenser unit (**J**). The data acquisition computer (**O**) was started just prior to the schedule beginning. The schedule (**Figure 3.3**) was begun as soon as possible after loading the kiln.

Sampling

Condensate samples from the heat exchanger drain line were collected every four hours during the schedule. The flow rate of condensated was measured by timing how long it took to collect 500 ml in a graduated cylinder. The condensate was

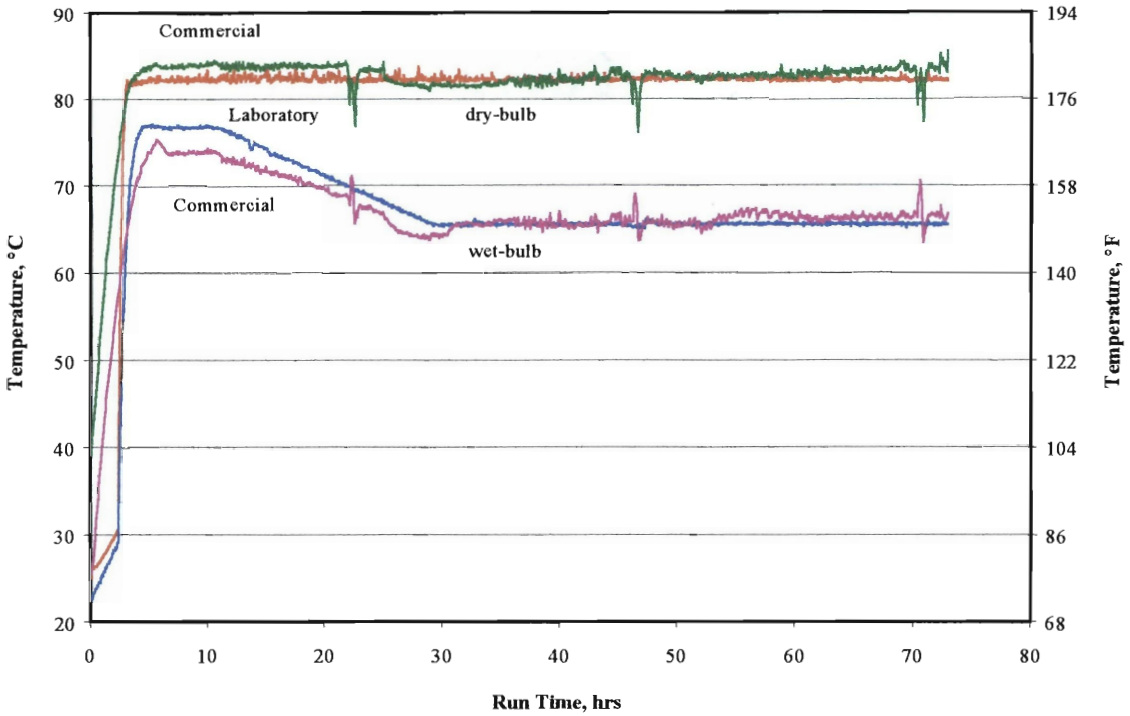


Figure 3.3 Matched drying schedules, laboratory and commercial, Douglas-fir. The laboratory kiln showed slightly better control with less variation in temperature. The commercial kiln had fan reversals so spikes in temperatures are present.

combined in 2000-ml Erlenmeyer flasks with ground glass mouth (Jüttner, 1986). The mouth of the flask, including the glass stopper was wrapped in Parafilm M® to ensure the stopper stayed in tight. The sealed flasks were stored in an ice-chilled cooler until organic extraction could be performed.

Placing a Teflon® coil inside a plastic 3-gallon cooler (**J**) created a condenser for an adsorption sampling train. Ice water was added to the cooler to chill the exhaust gas and condense water and less volatile water soluble organics. The condensate was collected in a water trap (**I**), 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.

Those organic molecules that remained volatile and were not collected in the condensate trap were passed through two Orbo™-32 activated charcoal tubes (Supelco Inc. #2-067) (**G**) in series. Organics adsorbed onto the surface of the "activated" porous structure of the charcoal. Since there is a finite capacity of activated charcoal

(Noyes, 1991), the charcoal was changed every few hours depended upon the concentration of reading of the THA. In the beginning of the schedule the venting/drying rate and hydrocarbon concentration were relatively high so 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 one hour. By the end of the schedule the hydrocarbon concentration in the exhaust had decreased to the point where the sampling interval was extended to up to six hours. As each tube was removed from the sampling line, its ends were capped which effectively isolated the charcoal in the glass tube and ensured that no more organics were collected or lost. The sealed tubes were stored in a Ziplock™ plastic bag placed in an ice-chest until organic extraction could be performed.

The THA (**D**) was zeroed and adjusted every few hours. Grade 5.0 Hydrogen was used for the ionization flame. The hydrogen regulator was set to 20 psig and the internal regulator of the system metered the gas to the ionization chamber as needed. Grade 5.0 Nitrogen was used for the zero gas and purge gas. The second stage of the nitrogen regulator was set to 15 psig and was metered into the ionization chamber to zero the system periodically through out the experiment. Propane at 885 ppmv in air was specially mixed for this experiment. 885 ppmv was set on the span calibration when the propane flowed through the detector. The maximum adjustment required was less than three percent of the reading.

After completion of schedule, the charge was pushed into the covered cooling area where it was broken down the next morning. The first two charges had the packages that were weighed green were again weighed to get their kiln dry weights. This was again done with the aid of a tared carrier truck. The boards from all three charges were processed by 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 in-line meter.

Laboratory Kiln

The laboratory kiln (**Figure 3.4**) had compressed house air (**N**), of known composition, metered into it by an MKS Instruments, Inc. 0-50 liter/minute Type 0558A mass flow meter (**L**) and Type 1559A mass flow controller (**M**). This gave a slightly higher than ambient pressure in the kiln. Flow through the meter was manually controlled, as needed, with a needle valve. The mass flow controller modulated the flow based on a signal from the computer, increasing the flow, as more venting was required. This meter was set to always have a minimum of 4.0 liters/minute flow, slightly more than that being drawn by the THA (3.0 liter/minute) and the adsorption sampling train (0.8 liter/minute).

Twenty-four hours before each laboratory kiln charge, four bundles representing a kiln charge were removed from the freezer and allowed to thaw for approximately 20 hours. Packages remained sealed in plastic to help retain any volatiles. Two hours before the scheduled beginning of the kiln run, the support gases (**A**,**B**,**C**) were turned on. The THA (**D**) was turned on and allowed to warm to its set-point temperature (190 °C) and the detector to stabilize. Just prior to loading the kiln, the four bundles of 48-inch lumber were unwrapped and each board was trimmed to 44-inches by trimming two inches from each end. This was done so the boards would fit into the kiln and 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 with ten courses on 0.75 inch stickers (**K**).

The data acquisition/controller computer (**O**) was booted; the specific control files were loaded and initiated. Laboratory kiln conditions were set to closely represent the commercial kiln schedule (**Figure 3.3**).

The laboratory kiln did not have a heat exchanger and thus the only condensate collected was in the water trap of the adsorption sampling train. The same procedure for collection and storage as detailed for the commercial kiln were followed for this condensate and the activated charcoal tubes (**G**). The THA drew its three liters/minute

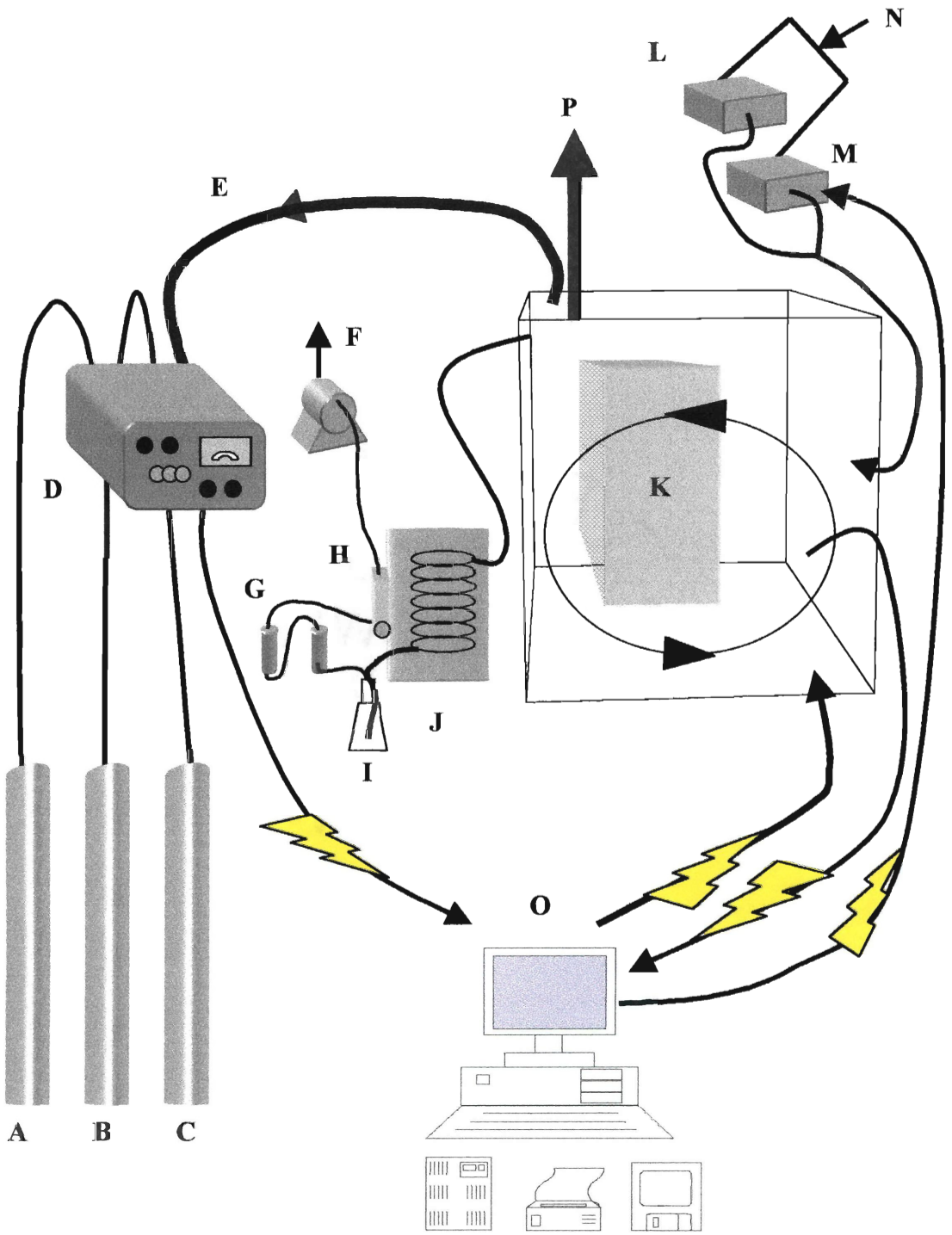


Figure 3.4 Laboratory kiln configuration. The charge of lumber (K) inside the kiln which is controlled and monitored by the data acquisition/controller computer (O), D represents the total hydrocarbon analyzer and A,B,C are the support gases. The adsorption sampling train (F,G,H,I,J) was used to collect samples for speciated analysis and the kiln make-up air inlet is represented by L,M,N.

directly from the kiln, instead of from the exhaust line. The performance of the THA was monitored and adjusted at every sampling interval just as during the commercial charge tests.

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.

Extraction Procedures

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

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 seal was crimped and the sample was stored at 4 °C (Federal Register, 1995; McDonald & Wastney, 1995; Quigley & Corsi, 1995; USATHAMA, 1990) in a dark environment. Chromatographic analysis was performed within two weeks collection (Bayne et al., 1994; Federal Register, 1995; U.S. EPA, 1994).

The glassware was rinsed between extractions with water, five-ml of HPLC grade methanol and finally five-ml standard dichloromethane solvent solution (Brown, 1971). Between rinsings the separatory funnel drained.

Activated Charcoal Tubes

The activated charcoal was removed from the glass tubes and transferred into correspondingly labeled two ml plastic Corning® Cryogenic screw top 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 with a Nichiryo repeater pipette set to position 1, with a 60-ml tip.

The vials were sealed with screw caps and placed into a small beaker such that the sample vials remained upright during 15 minutes of sonication. After sonication, the liquid fraction was removed from the vials using a 10-ml glass Micro-Mate® syringe with a 16-gauge metal Luer-lock tip. A non-sterile Millex-FG_{13} 0.2-µm filter was used to ensure the samples were free of particulates. Typically, less than one ml of solvent/sample was collected because some solvent remained wetting the charcoal. This extraction process was repeated and the extractant was combined with the extractant from the first extraction procedure in an auto-sampler crimp seal vial. The Teflon®-lined silicone crimp seals were crimped onto the mouth of the vial and the samples were stored below 4 °C (Federal Register, 1995; McDonald & Wastney, 1995; Quigley & Corsi, 1995; USATHAMA, 1990) in a dark environment until analysis (Bayne et al., 1994; Federal Register, 1995; U.S. EPA, 1994).

GC-MS Analysis

A Hewlett Packard 7673 GC auto-sampler injector manipulating a Hamilton 10uL #80377 syringe (Hamilton Co., Reno Nevada) drew two-µL of sample from each sample vial and injected it through a septa, into the injector port of a Hewlett Packard 5890 Series II Gas Chromatograph. The syringe barrel was thoroughly flushed between sample injections. The split/splitless injector port was controlled to a temperature of 200 °C (392 °F). A split ratio of 1:20 was used to avoid the potentially large solvent tail.

The carrier gas was Grade 4.7 Helium set to a flow rate of 1.02 ml/minute into the 60 meter Supelco 10 column (0.2 mm I.D., phase film 0.2 µm, Catalog # 2-4170

Supelco Bellefonte, PA, USA). The GC oven was programmed to hold at 70 °C for 2 minutes, ramp at 6 °C/minute to 210 °C, then hold for 18 minutes. The separated unknown VOC components moved to a Hewlett Packard 5971 quadrupole mass selective detector (mass spectrophotometer) set to an ionization energy of 70 eV with the transfer line and ion source set to 280 °C and 180 °C respectively. Identification of the individual components of the samples were determined by retention time and comparison of mass spectra with the NIST/EPA/MSDC 54K Mass Spectral Library and Hewlett Packard MS Chemstation (Catalog #HP G1030A).

Both internal and external standards were used to confirm compound identification and to quantify results. The detector sensitivity to each compound was determined by running a mixture of knowns, making possible accurate quantification of the unknowns. The internal standard was one g/liter undecane added to the dichloromethane (standard dichloromethane solvent solution). The external standards were known concentrations of individual anticipated monoterpenes, and a known mixture of these monoterpenes.

Calculations

The calculation procedure used to determine the dry gas flow rate, moisture content of the wood, hydrocarbon emissions, and monoterpene emissions from the kiln is schematically represented in **Figure 3.5**. Summing the emissions from each time 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.

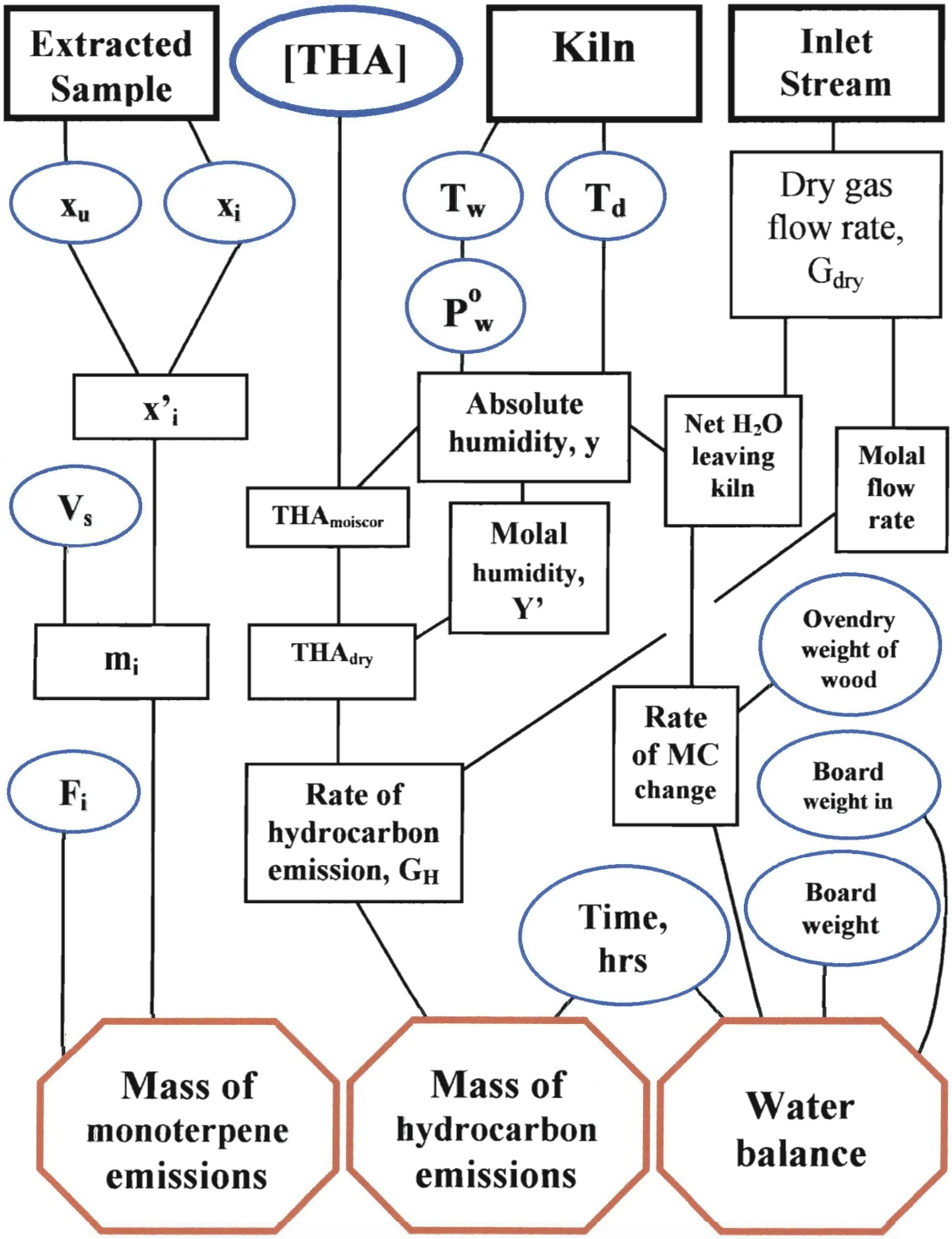


Figure 3.5 Calculation procedure. Measured variables are in ovular shaped fields, calculations and collected samples are in rectangular fields, and the results are in the octagonal fields.

Humidity

Vapor pressure was calculated for the wet-bulb in the kiln (Yaws, 1977)

$$P_w^0 = \left(\frac{101325\,Pa}{760\,mmHg}\right) 10^{16.373 - \frac{2818.6}{T+273.16} - 1.6908\log(T+273.16) - 0.005754*(T+273.16) + 4.0073*10^{-6}*(T+273.16)^2} \quad (1)$$

where, T is the wet-bulb temperature (°C) inside the kiln. The absolute humidity inside the kiln was calculated as:

$$y = \frac{MW_{water}}{MW_{air}} \frac{1}{\frac{p}{\frac{\Psi_C}{100} * p_w^0} - 1} - \left((T_{DB} - T_{WB})\left(\frac{h_g / k_y}{\lambda}\right)\right) \quad (2)$$

where p=101,325 Pa, Ψ_C=100%, h_g/k_y=0.95kJ/(kg-K), and λ=2419.3kJ/kg. The molal humidity inside the kiln was calculated as:

$$Y' = \frac{MW_{air}}{MW_{water}} * y \quad (3)$$

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:

$$X_n = X_o - 100 * \frac{\sum_{j=1}^{j=n} G_j * y_j * \Delta t_j}{m_{OD}} \quad (4)$$

Total Hydrocarbon Analysis

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

$$THA_{moiscor} = \left[\frac{THA}{(1 - A)^{E*y+A}} \right] \quad (5)$$

where A = 0.79 and E = -6.649. These values were 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:

$$THA_{dry} = THA_{moiscor} * (1 + Y') \quad (6)$$

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

$$G_H = (G') \left(\frac{THA_{dry}}{1{,}000{,}000} \right) (MW_{propane}) \left(\frac{1{,}000g}{1kg} \right) \quad (7)$$

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

$$m_H = \sum_{j=1}^{n} G_{H_j} * \Delta t_j \quad (8)$$

where n corresponds to the interval at which the wood moisture content is 12% as determined by equation 4.

Adsorption Sampling Train

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:

$$X'_i = \frac{1{,}000 \frac{g}{\ell}}{x_u} * x_i \tag{9}$$

where i represents the i^{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.

$$m_i = X'_i * V_s \tag{10}$$

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

$$M_i = \sum_{j=1}^{n} \left(\frac{G'_j}{G'_{CH_j}} \right) * (m_i)_j \tag{11}$$

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

Specific Gravity

The specific gravity (SG) of the laboratory samples was calculated

$$SG = \frac{m_{OD}}{L * W * D * \rho_{H_2O}} \tag{12}$$

where m_{OD} is the weight of the oven dry wood (g), ρ_{H_2O} is the density of water, and length (L), width (W), and thickness (D) are in meters.

Results and Discussion

Wood Properties

Analysis of the packages of lumber used in the laboratory kiln revealed (**Table 3.1**) 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 oven dry lumber, where as the calculations for the commercial charges are based upon moisture meter readings. 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.

The initial moisture content of the charges did not play a major role in the total cumulative emissions (**Figure 3.6**), however, initial moisture contents did not var 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_{ODwood}. Analysis of these lumber charges by adsorption of volatiles with activated charcoal revealed total monoterpene emissions of approximately 0.2 g/kg_{ODwood}.

Commercial Kiln Results

Total Hydrocarbon Analyser

The hydrocarbon concentration in the exhaust air increased rapidly from near zero to 2,883 ppmv at approximately six hours into the schedule when venting began (**Figure 3.7**). The concentration in the 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.

Table 3.1 Wood properties, Douglas-fir. Physical parameters of the 2x6 Douglas-fir lumber used in the kiln emission study. Cumulative emissions, g/kg_{ODwood}, 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.

Sample Length = 44 inches							
Charge ID		Green MC %	Heart %	Rings #/inch	Specific Gravity	g Monoterpene kg OD Wood @ 12 % MC	g THC kg OD Wood @ 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
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		

After venting began at the six-hour point in the schedule, the hydrocarbon concentration rapidly decreased. As the venting rate increased (**Figure 3.7**) the emissions rate remained almost constant from hour six to hour 25 in the schedule. This is demonstrated by the linear part of the cumulative emissions curve (**Figure 3.8)**

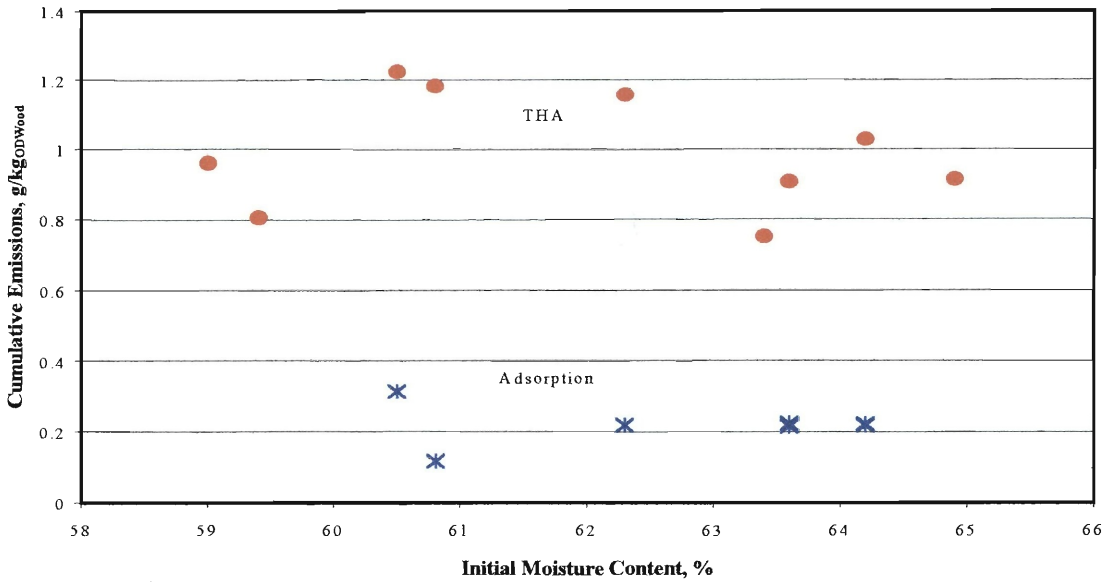


Figure 3.6 Cumulative emissions vs. initial moisture content, Douglas-fir. Cumulative emissions, g/kg, from commercial and laboratory charges dried to 12% moisture content reported versus their initial moisture content.

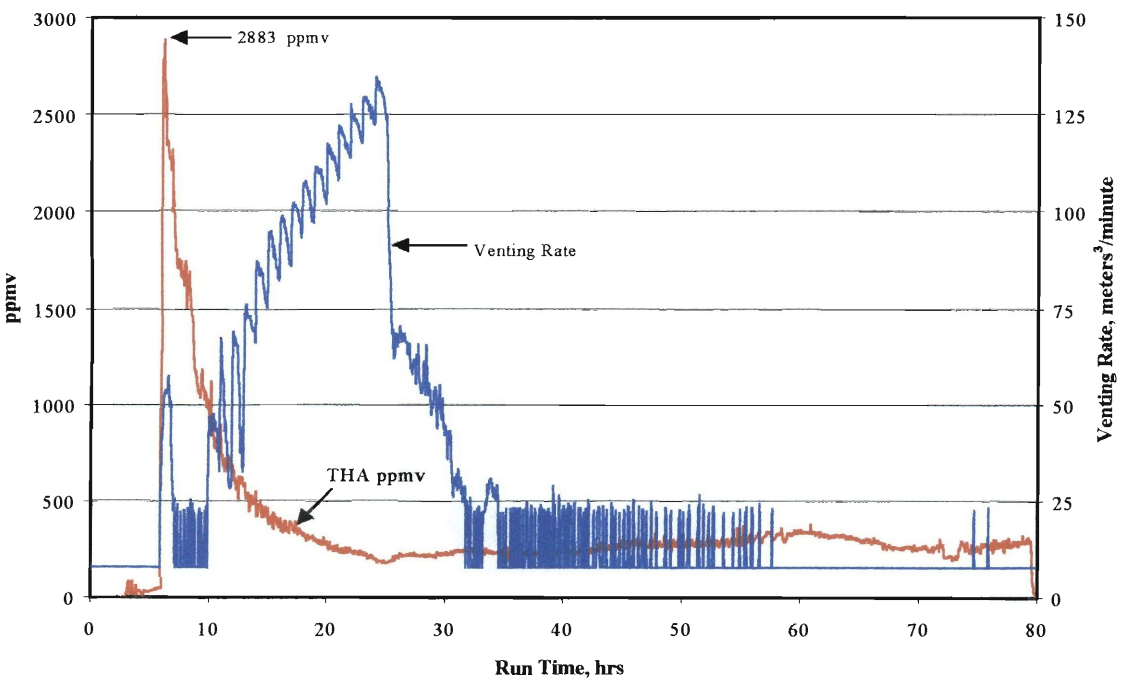


Figure 3.7 Cumulative emissions and venting rate, Douglas-fir. Commercial kiln charge 2, 2x6 Douglas-fir, with THC reported on a dry gas basis in parts per million volumetric basis compared to the venting rate, cubic meters per minute.

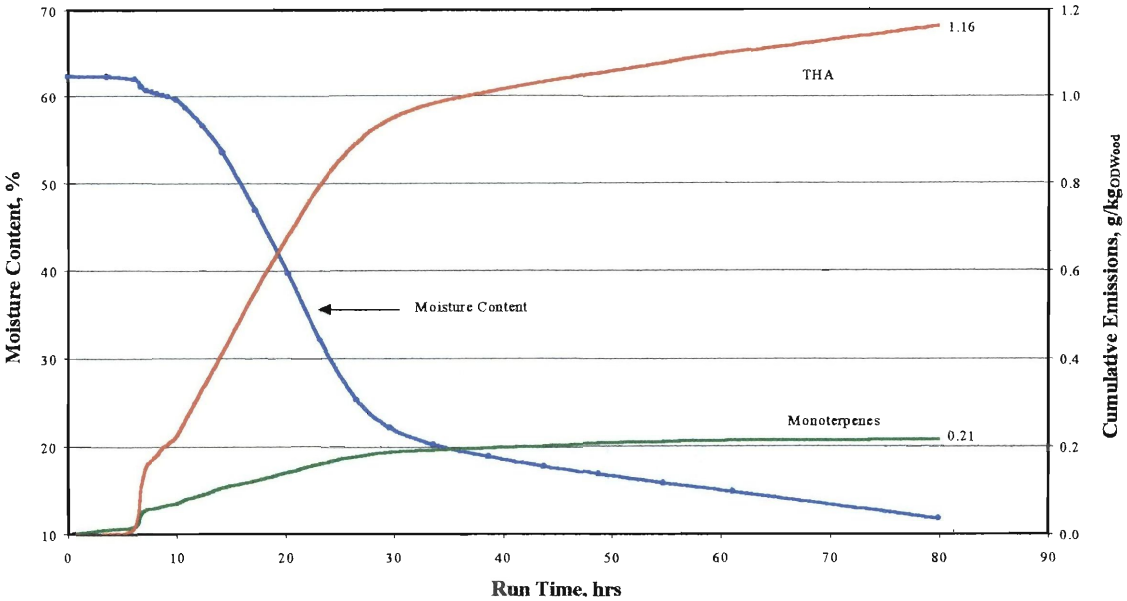


Figure 3.8 Cumulative emissions and charge moisture content, Douglas-fir. Commercial charge 2, 2x6 Douglas-fir, dried to 12% moisture content and the moisture content of the charge.

Between hours 25 and 36 the emissions rate decreased, rapidly as indicated by the knee in the cumulative emissions curve (**Figure 3.8**). For the remainder of the drying schedule the emissions rate decreased slowly.

The total quantity of hydrocarbons released averaged 1.07 g/kg$_{ODwood}$ (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 know if the difference is due to actual variability of the VOCs released or sampling error. This measured unit emissions is 2.5 times the value reported for Douglas-fir heartwood by NCASI (0.43 g/kg$_{ODwood}$) and 7.6 times the value they reported for emissions from sapwood (0.14 g/kg$_{ODwood}$). Wu (1997) reported 0.99 g/kg$_{ODwood}$ on a dry gas basis for coastal Douglas-fir dried in a laboratory kiln using a similar schedule.

Between hours 12 and 24, as the moisture content of the wood decreased rapidly, the cumulative emission increased rapidly (**Figure 3.8**). 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 3.9**) 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, 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.

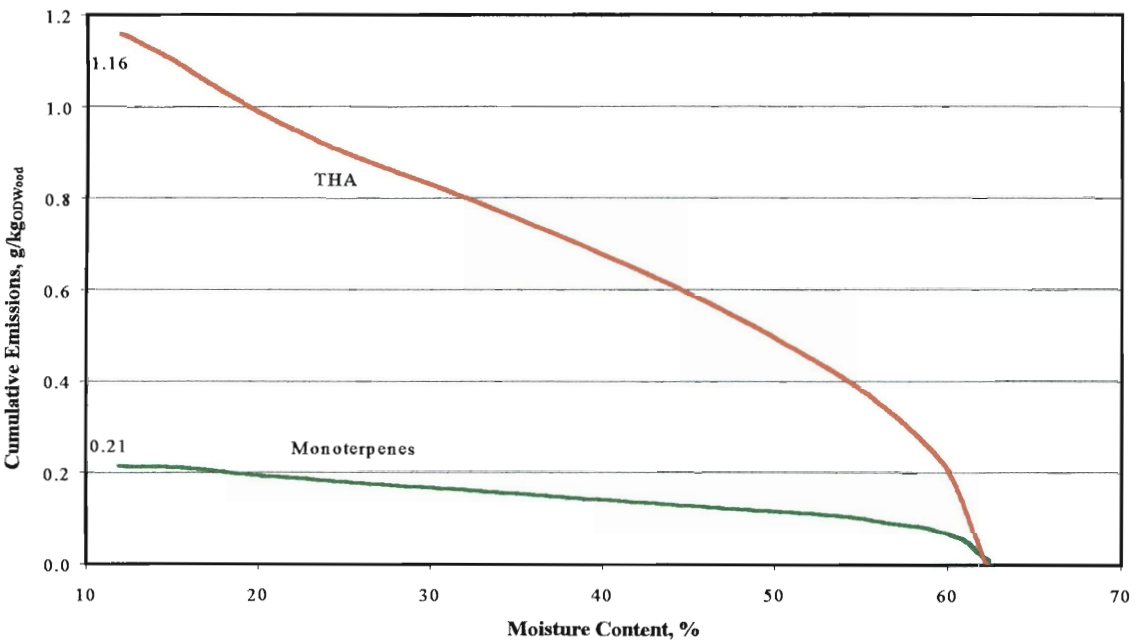


Figure 3.9 Cumulative emissions vs. moisture content, Douglas-fir. THC from commercial charge 2 compared to moisture content of the 2x6 Douglas-fir charge.

Monoterpenes

Speciated information for commercial kiln run 2 indicates that α-pinene is the dominantly emitted monoterpene (**Figure 3.10**). α-pinene is expected to be the most abundant species because it is a present in relatively high concentrations in conifers.

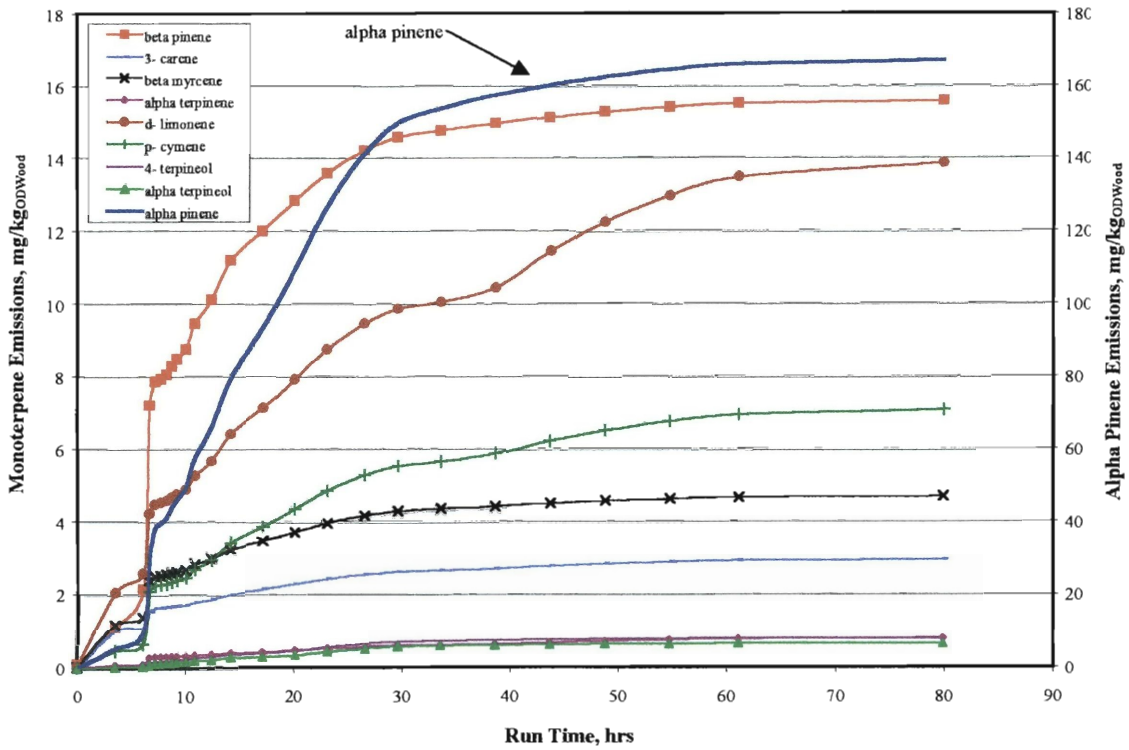


Figure 3.10 Cumulative speciated monoterpene emissions, Douglas-fir. Commercial charge 2, 2x6 Douglas-fir, dried to 12% moisture content.

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 α-pinene being detected in concentrations several times greater than the others. Initially there was a high rate of monoterpene emissions but as the schedule continued the rate deceased. This trend mirrors the tend 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_{ODwood}, where as in run two only 0.22 g/kg_{ODwood} was collected. Wood properties do not seem to explain the difference in total monoterpenes collected because **Table 3.1** indicates that the properties were similar. The schedules run appear to hold a potential explanation (**Figure 3.11**). The dry-bulb temperatures for commercial kiln runs one and two were

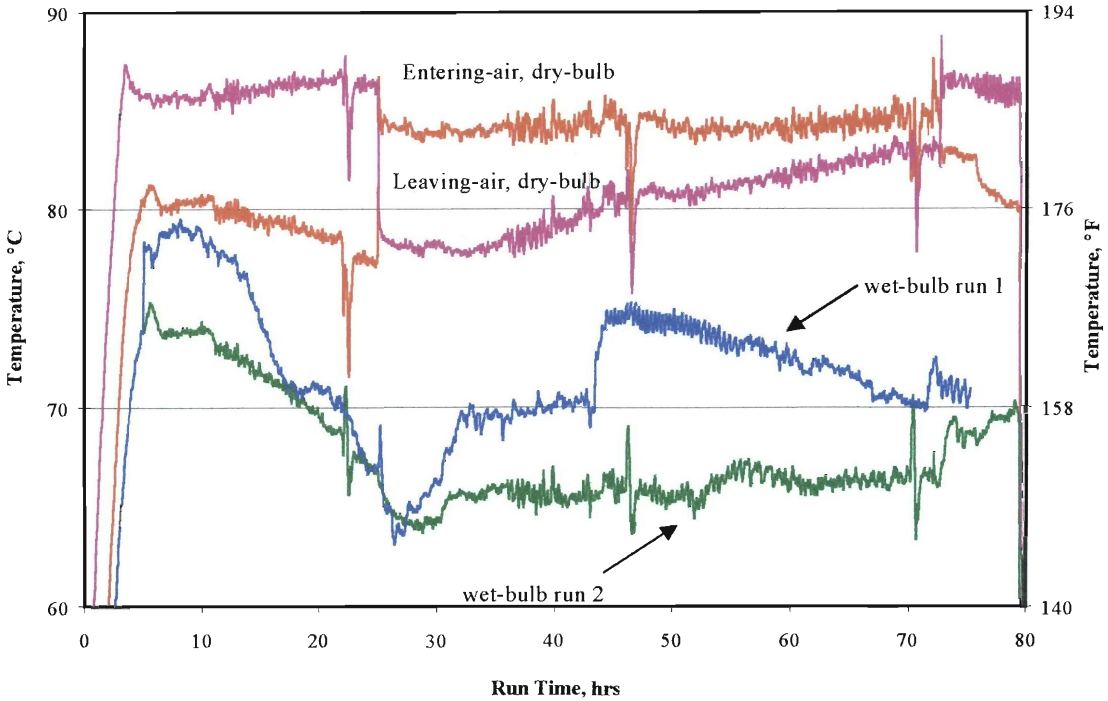


Figure 3.11 Wet-bulb depression, commercial schedules. Representative entering and leaving dry-bulb temperatures and wet-bulb temperatures from commercial kiln runs one and two. Kiln run one had a lower wet-bulb depression then kiln run two.

almost exactly the same, however the wet-bulb temperatures were not. During run one the wet-bulb temperature initially went up to 79 °C where in run two it only went up to 74 °C. The two temperatures were then similar between hours 20 and 30. After the 13 hours the wet-bulb temperature for commercial kiln run one began to increase, decreasing the wet-bulb depression. This decreased wet-bulb depression during much of the schedule may, in part explain the greater amount of monoterpenes detected. If the lumber was dried under more severe drying conditions it is possible that more monoterpenes were volatilized from the wood. However, Wu (1997) did not find wet-bulb depression to have an effect on total emissions.

Heat Exchanger Condensate

There were only two monoterpenes identified in the condensate from the heat exchanger, α-terpineol (0.029 mg/kg_{ODwood}) and 4-terpineol (0.014 mg/kg_{ODwood}). A

total of 1,193 liters of water was calculated to be condensed in the heat exchanger and approximately 0.043 mg/kg_{ODwood} of monoterpenes. α-terpineol is slightly soluble in water. The only other monoterpene, of those detected in the exhaust stream, which is also soluble in water is α-pinene. However, the boiling point of α-pinene is 156.2 °C as compared to 217.5 °C for α-terpineol. The temperature of the condensate leaving the heat exchanger was 43.3 °C. It is likely that this temperature was high enough to volatilize a significantly larger portion of the α-pinene such that it was undetected.

Lab Results

Total Hydrocarbon Analyser

The venting rate and hydrocarbon concentration in the laboratory kiln (**Figure 3.12**) affects the THC emissions (**Figure 3.13**) in a similar manner as in the commercial kiln (**Figures 3.8** and **3.9**). The hydrocarbon concentration in the exhaust air increased rapidly from near zero to more than 3,500 ppmv at approximately six hours into the schedule when venting began (**Figure 3.12**). The hydrocarbon concentration in the kiln likely increased over this six-hour time interval due to the kiln not venting.

After venting began at the six-hour point in the schedule, the hydrocarbon concentration rapidly decreased. Simultaneously the venting rate increased (**Figure 3.12**) resulting in an emissions rate that was almost constant from hour eight to hour 28 of the schedule. This is demonstrated by the linear part of the cumulative emissions curve in **Figure 3.12**.

Between hours 28 and 36 the emissions rate decreased, rapidly as indicated by the knee in the cumulative emissions curve (**Figure 3.13**). For the remainder of the drying schedule the emissions rate slowly decreased.

The total quantity of hydrocarbon emissions averaged 0.96 g/kg_{ODwood}, with a standard deviation of 0.169 g/kg_{ODwood}, for the eight laboratory kiln charges. Results

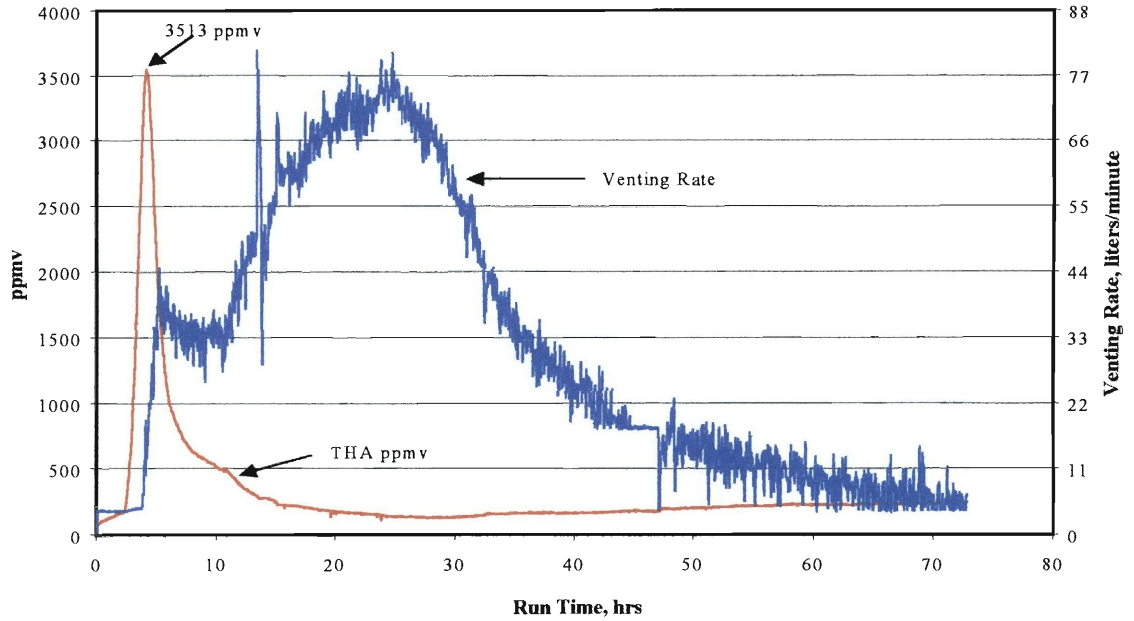


Figure 3.12 Cumulative emissions and venting rate, laboratory, Douglas-fir. Emissions from, 2x6 Douglas-fir, reported on a dry gas basis in parts per million volumetric basis compared to the venting dry gas flow rate, liters/minute.

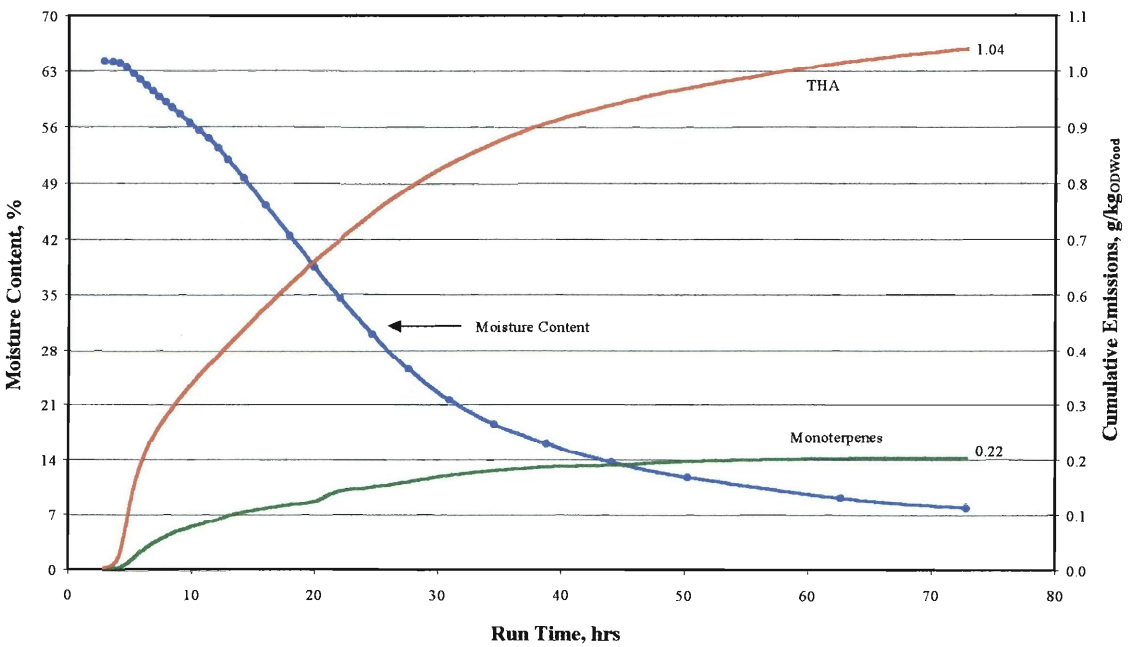


Figure 3.13 Cumulative emissions and charge moisture content, laboratory, Douglas-fir. Emissions from laboratory charge 5, 2x6 Douglas-fir, dried to 12% moisture content and the moisture content of the charge.

indicate, with 95% confidence, that the laboratory kiln, drying 2x6 Douglas-fir, will emit between 0.85 g/kg_{ODwood} and 1.08 g/kg_{ODwood} of total hydrocarbon.

It is not known if the difference is due to actual variability of the VOCs released or sampling error. This measured ratio of emissions is 2.25 times the value reported for Douglas-fir heartwood by NCASI (0.43 g/kg_{ODwood}) and 6.9 times the value they reported for emissions from sapwood (0.14 g/kg_{ODwood}). Wu (1997) reported 0.99 g/kg_{ODwood} on a dry gas basis for coastal Douglas-fir dried in a laboratory kiln using a similar schedule.

Between hours 8 and 30, as the moisture content of the wood decreased rapidly and the cumulative emission increased rapidly (**Figure 3.13**). 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 the moisture content of the charge. When cumulative emissions are plotted as a function of moisture content (**Figure 3.14**) it is clear that the quantity of emissions released was nearly proportional to the change in moisture content from when the charges moisture content is approximately 53% to the end of the schedule. Even though many of the volatile compounds released from Douglas-fir as it dries are not soluble in water it is possible that they may move to the surface of the drying lumber 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

Laboratory analysis of the monoterpenes in the exhaust line show that α-pinene is the dominant species emitted (**Figure 3.15**). This is the same trend shown in the commercial kiln study and in the literature. The relative ratios of each monoterpenes emitted are similar between laboratory charges. α-pinene is the dominant species emitted, showing emissions an order of magnitude greater than the next most abundant emittant, β-pinene.

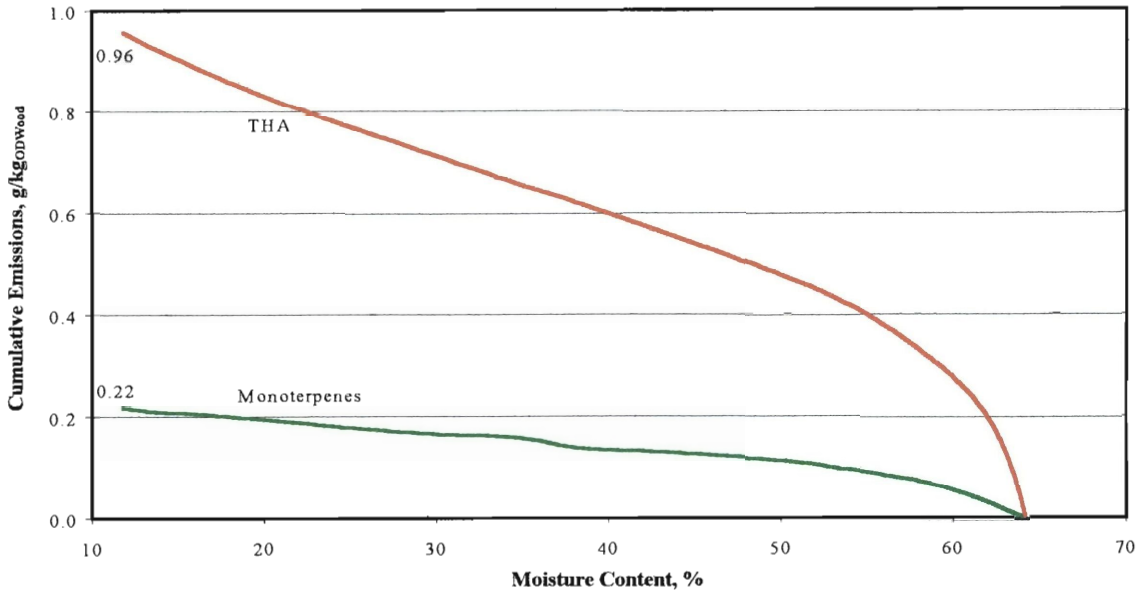


Figure 3.14 Cumulative emissions vs. moisture content, Douglas-fir.

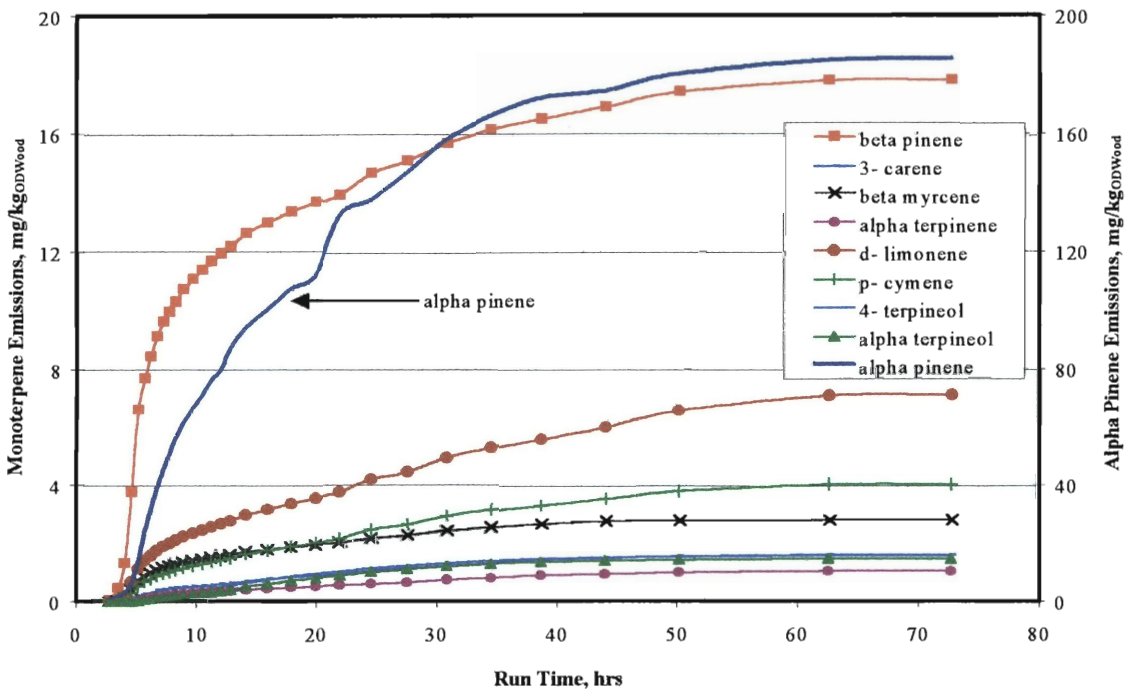


Figure 3.15 Cumulative speciated monoterpene emissions, Douglas-fir. Emissions from laboratory charge 5, 2x6 Douglas-fir, dried to 12% moisture content.

Comparisons Between Commercial and Laboratory Kiln

The laboratory kiln performs like a scaled down version of the commercial lumber dry kiln in many respects. The venting versus time in each kiln follows a very similar pattern, as shown in **Figures 3.7** and **3.12**. In addition, the peak hydrocarbon concentrations were similar, approximately 2900 ppmv in the commercial kiln and 3500 in the laboratory kiln. Each of these peak concentrations is achieved as venting begins 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 (**Figures 3.14** and **3.16**) the same profile is seen for the laboratory and commercial kiln.

Similar total amounts of hydrocarbon emissions were released, and average of 0.96 g/kg_{ODwood} from the laboratory kiln and 1.07 g/kg_{ODwood} from the commercial kiln. A two-tailed p-value from a t-test attempting to show a difference between the population means of the laboratory and commercial kiln total emissions is 0.47. This very large p-value is convincing evidence that a difference between the total hydrocarbon emissions from the laboratory kiln and commercial kiln can not be shown. Additional replicates may help to strengthen this model but in environmental field sampling agreement of between 10 and 20% is considered good. In addition, the GC-MS analyzer indicated that the monoterpene emissions from each kiln were emitted in similar ratios.

All this 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.

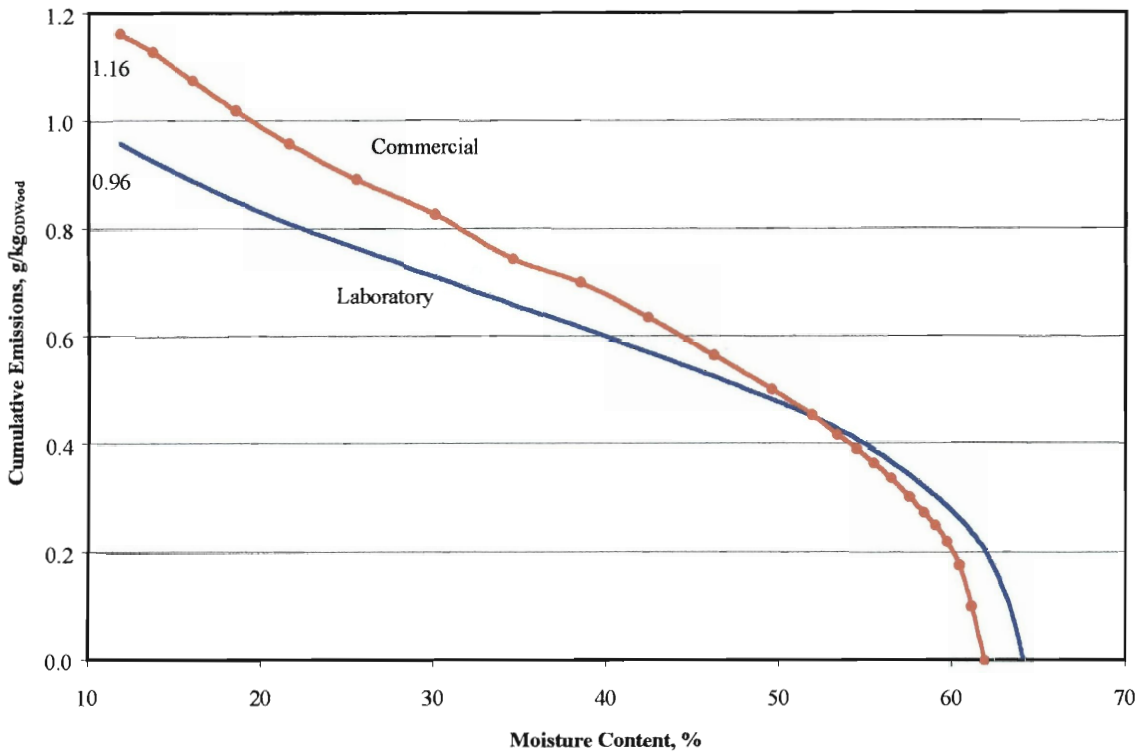


Figure 3.16 Cumulative emissions, laboratory and commercial kilns. Laboratory charge 5 started out at a slightly higher moisture content and ended up emitting slightly less THC than commercial charge 2.

Conclusions

Total emissions released from both the laboratory and commercial kiln charges was successfully monitored. Analysis of the emissions revealed approximately 1.0 g VOC / kg oven dry 2x6 Douglas-fir. This indicates that the laboratory kiln can be used to accurately predict total emissions from a commercial kiln without having to use an adjustment factor. This avoids the waste and uncertainties of large scale testing.

Analysis of speciated emissions revealed that qualitative and quantitative comparisons between the commercial kiln and laboratory kiln are valid. The relative ratios of monoterpenes is the same for both kilns. However, the total emissions detected for monoterpene emissions is five times smaller than detected with THA analysis. This is likely due to non-monoterpene compounds not being detected, and analyzed for, such as di-terpenes and hemi-terpines.

The results from this study should affect the forest products industry's thinking on Title V (permit acquisition) issues because their emissions are potentially greater than previously assumed. The methods in this study can be used to determine the quantity of emissions expect when drying 2x6 Douglas-fir with a standard commercial schedule. Accurate determinations of emission quantities will enable more precise matching of permits to actual emissions quantities.

CHAPTER IV VOC Emissions from Ponderosa Pine Comparing a Commercial and a Laboratory Kiln

Abstract

The 1990 Amendments to Title V of the Clean Air and Clean Water act are forcing emitters of volatile organic compounds to obtain operating permits based upon the quantity and species of emissions produced. Operators of lumber dry kilns are subject to Title V permitting due to the volatile organic compounds emitted from lumber as it dries. This research project compared a commercial lumber dry kiln with a laboratory lumber dry kiln. The results showed that when drying matched charges of ponderosa pine the commercial kiln emitted 2.82 g/kg_{ODwood} (5.20 lbs/mbf) while the laboratory kiln emitted an average of 1.97 g/kg_{ODwood}. Even though the laboratory kiln under estimated emissions from the commercial kiln, the laboratory method may still be a representative model of a commercial scale lumber dry kiln, if an appropriate scale up factor is used. The use of the laboratory kiln is much more efficient for monitoring emissions because of its location, size of lumber charge, and proximity to laboratory analysis equipment. The small size of the lumber charge makes it possible to economically test various schedules quickly and to compare emission rates[3].

[3] The author wishes to acknowledge Boise Cascade at Emmett, ID and CSI Carter Sprague in Beaverton, OR for assistance on the project. This work was funded by USDA Competitive Grant 95-37500-2302.

Introduction

Increasing human population, with its ever-increasing need and desire for products, is leading to an increase in manufacturing. Not only does this population require more and more manufacturing production, and therefore resource exploitation, it vocally 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 these processes. Regulations and public attention are forcing the industry to address the issue of volatile organic compound (VOC) emissions by installing costly emission control technologies.

The lumber industry has great interest in the amount of hydrocarbon being emitted from their drying process because of the expense of EPA Title V permitting issues. The Clean Air Act (CAA) states that it is necessary to describe dry kiln emissions such that potential Hazardous Air Pollutants (HAP) sources as well as benign VOC emission sources. HAPs can cause serious health and environmental effects including; cancer, birth defects, nervous system disorders, and even death.

The desire for a clean process and the fear of noncompliance are forcing kiln operators to obtain Title V permits based upon quantities of emissions that are potentially greater than they actually release. Until recently (Ingram et al., 1995a; NCASI, 1996; Wu, 1997) commercial kiln operators had little to no scientific knowledge of the quantity of emission being released from lumber dry kilns as the charge of lumber was dried to target moisture content (MC). In fact there are no published studies detailing the emission quantity from commercial kilns. This study directly addressed this data void by monitoring the emissions from a commercial kiln.

Increasingly, states are asking for speciated VOC information in addition to total hydrocarbon (THC) measurements. There are no published studies describing the

emission spectra expected in the exhaust. It is believed that a major component of the emissions released during lumber drying are VOCs, and in particular monoterpenes ($C_{10}H_{16}$), those substances our noses identify as the smell of wood. The major monoterpenes (β-pinene and α-pinene) are expected to be emitted from a kiln during the peak drying rate of the kiln schedule (McDonald & Wastney, 1995), i.e. during the initial six hours of the schedule (Ingram et al., 1995a; Wu, 1997).

Monitoring a commercial kiln is time consuming, logistically difficult, and thus expensive. This study addressed the issue of kiln drying capacity and expected emission rates. The emissions from a commercial kiln and those from a laboratory kiln were compared using the same equipment and methods. A strong understanding of the emissions pattern and the relationship between the commercial scale and laboratory kiln may enable emissions analysis to be conducted in the laboratory, providing a great service to the industry. The laboratory kiln's small scale and highly controlled environment are ideally suited to test a diverse species set and drying schedule library efficiently and economically.

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

Literature Review

Kilns emit many different VOC 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, since the chemical composition varies among species.

The species of emissions are likely to be condensation polymers of isoprene. These compounds are predominately monoterpenes ($C_{10}H_{16}$) of different configurations such as α-pinene, β-pinene, limonene, camphene, and myrcene (Cronn et al., 1983; Ingram et al. 1995a; McDonald & Wastney, 1995). These monoterpenes have boiling points of approximately 155 °C 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.

Emissions from lumber dry kilns are difficult to quantify because of their design. Often there are multiple sites of venting and many avenues for fugitive gas to escape detection, such as around the door seals. Most kilns have modulated control and no sufficient length of straight duct to conduct velocity profile measurements. No data was found in the open literature reporting emissions from lumber dried in commercial scale kilns. There were several studies published focusing on emissions from lumber dried in laboratory scale kilns. Sampling the exhaust stream of a charge of southern pine dried at 82.2 °C and 118.3 °C, with a flame ionization detector (FID), Ingram et al. (1995b) reported emissions of 2.75 g/kg_{ODwood}. Chemical analysis of the volatiles condensed from radiata pine dried at 120 °C and 140 °C revealed 0.23 and 0.32 g/kg_{ODwood} 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_{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, 0.99 g/kg_{ODwood} for sugar pine, 1.0 g/kg_{ODwood} for ponderosa pine, 1.29 g/kg_{ODwood} for western white pine, and 1.02 g/kg_{ODwood} and 1.53 g/kg_{ODwood} 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_{ODwood} of emissions were released from southern pine as it is dried. The limited literature on condensing volatiles indicates that studies

conducted with a FID may report higher emission rates than those determined by condensing. This may be due to more complete detection with the FID.

Materials and Methods

Commercial Charges

Two charges of freshly sawn, random width, ponderosa pine (*Pinus ponderosa*), were dried in a commercial kiln. The wood was sawn at a remote sawmill, solid-piled, then transported by rail to the site housing the kilns. 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.

Laboratory Charges

The lumber sampled for drying in the laboratory kiln was selected to be representative of that in the commercial charges. 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 16-foot lumber was cut into 48-inch pre-samples with a chain saw. The 48-inch pre-sample boards were systematically randomized into four piles (**Figure 4.1**). There were two sets of matched charges created for each corresponding commercial kiln charge. Each future charge of 48-inch lumber was tightly wrapped in plastic (0.006 inch thick clear) and the seams were sealed with duct tape. The wrapped lumber was kept to a manageable weight and size by wrapping five boards to a bundle, so there were four bundles for a lab kiln charge. Each bundle was labeled with a date and a laboratory charge identification number. The 16 bundles were then transported,

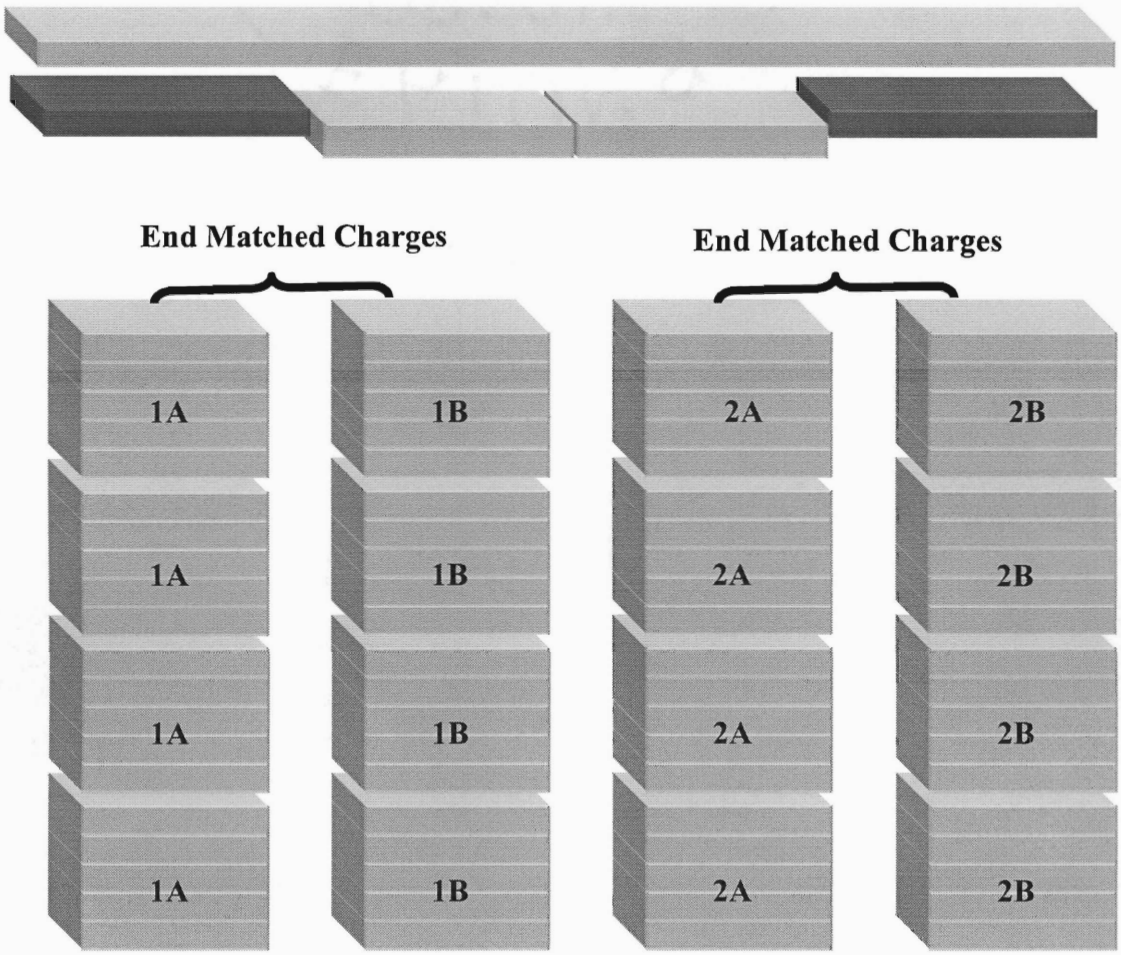


Figure 4.1 Lumber sampling, ponderosa pine. 16-foot random width ponderosa pine boards were sawn into 48-inch boards as detailed. The two sample boards from each board were placed in of the matched charges, one board in each pile.

in a pick-up truck, to the Forest Research Laboratory at Oregon State University and placed into a freezer (-15 °C) until the laboratory kiln charges were run.

Commercial Kiln

Kiln Configuration

The charges for the 68000 board foot, single-track kiln were crib stacked. A charge consisted of four 16-foot long packages. The kiln was equipped with a heat exchanger (**Q in Figure 4.2**) located on a suspended platform at mid-kiln length on the

cement kiln roof. The support gas cylinders (**A,B,C**) were secured to the welded structure of the platform and the gas lines were plumbed to the total hydrocarbon analyzer (THA) (**D**) with Teflon tubing. The test section of duct (**R**) was inserted in to the exhaust line prior to the heat exchanger (**Q**). The sample section of duct work consisted of a series of fins (**T**) which straightened the exhaust flow (**L** and **M**) and had a series of sealable sampling ports (**S**) at 60° intervals. Exhaust gas left the heat exchanger (**P**) and was replaced with ambient air (**N**). The sampling equipment for chemical analysis consisted of an ice chilled condenser (**J**), a water trap (**I**), two activated charcoal tubes (**G**), a flow meter (**H**) and a small pump (**F**). Sample exhaust was supplied to the THA through a 15-foot heated sampling line (**E**).

Temperature and Relative Humidity Sensors

A relative humidity sensor and thermocouple were placed under the eave of the control building. The solid state sensor was wired directly to the monitoring computer for data acquisition. It was located under the eave in order to protect if from the elements but to keep it 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.

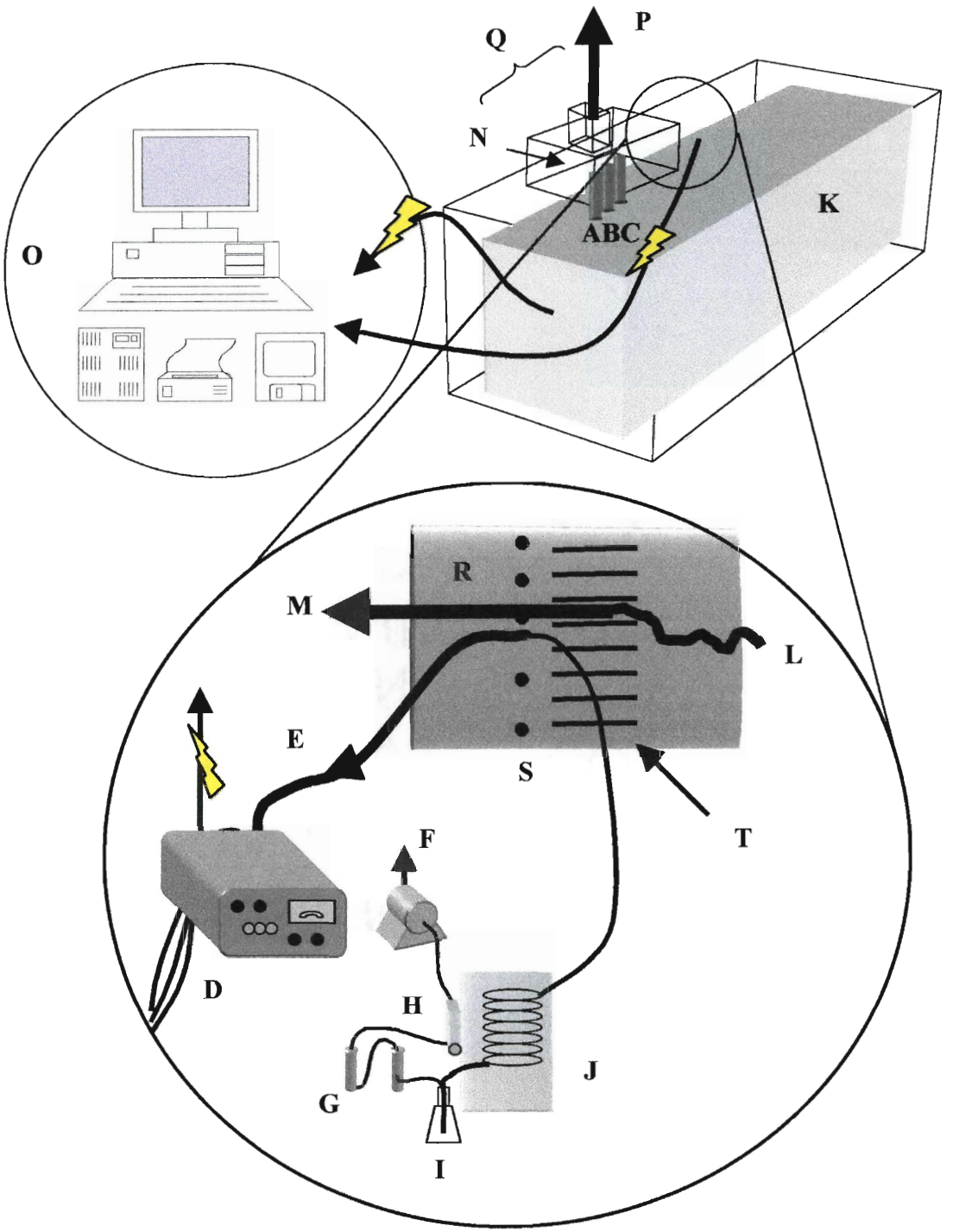


Figure 4.2 Commercial kiln configuration, ponderosa pine. The package of lumber (K) inside the kiln, the heat exchanger (Q), the data acquisition computer (O), the total hydrocarbon analyzer (D) and its support gases (A,B,C), the adsorption sampling train (F,G,H,I,J) and the test section of horizontal duct (R).

Dampers and Blower

The exhaust from the heat exchanger (**Q**) was controlled by a 3-15 psig air pressure signal from the kiln controller. At three psig, the dampers began to open and at 15 psig they were fully open. The blower was either on or off, depending upon the signal. As the air signal pressure was increased, the blower came on at approximately nine psig. The blower would remain on until the air signal was less than approximately six psig for three minutes. A pressure sensor ahead of the blower indicated if the blower motor was on or off.

Measurements were made in the commercial kiln at operating temperature in a loaded configuration prior to the study to determine the relationship between airflow and the air signal and blower status. The damper position, controlled by the air signal, had very little effect on the gas flow rate. Therefore, airflow during the study was based on the blower status. The kiln vented 2.65 m^3/s when the blower was on and 0.19 m^3/s when the blower was off. Fan direction in the kiln had no effect on the readings.

Sampling Modifications

A 24-inch section of 24-inch diameter horizontal duct (**R**), between the kiln and the heat exchanger was removed and replaced with a section containing a flow straightener (**T**), pitot sampling ports (**S**) around the circumference and a fixed three-holed rake type sampling probe. The flow straightener was a series of metal plates, parallel to the exhaust flow direction, welded in a web pattern. This pattern gave a uniform velocity profile across the diameter of duct and enabled flow measurements of the exhaust using a pitot tube. Sealable entry ports (**S**) were located every 60 degrees around the circumference of the duct to afford access to the exhaust stream for the pitot tube. The pitot tube was left in place during the test and data collected as a back-up procedure to monitor the blower status and damper position for measuring the exhaust gas flow rate. The fixed rake-type sampling probe was a stainless steel tube with three $^1/_{16}$ inch diameter holes drilled on one side of the tube, at the center and

16.7% of the diameter of the stack from each end. The sampling probe was located after the flow straighteners with the holes facing into the flow of the exhaust.

Start-up Procedures

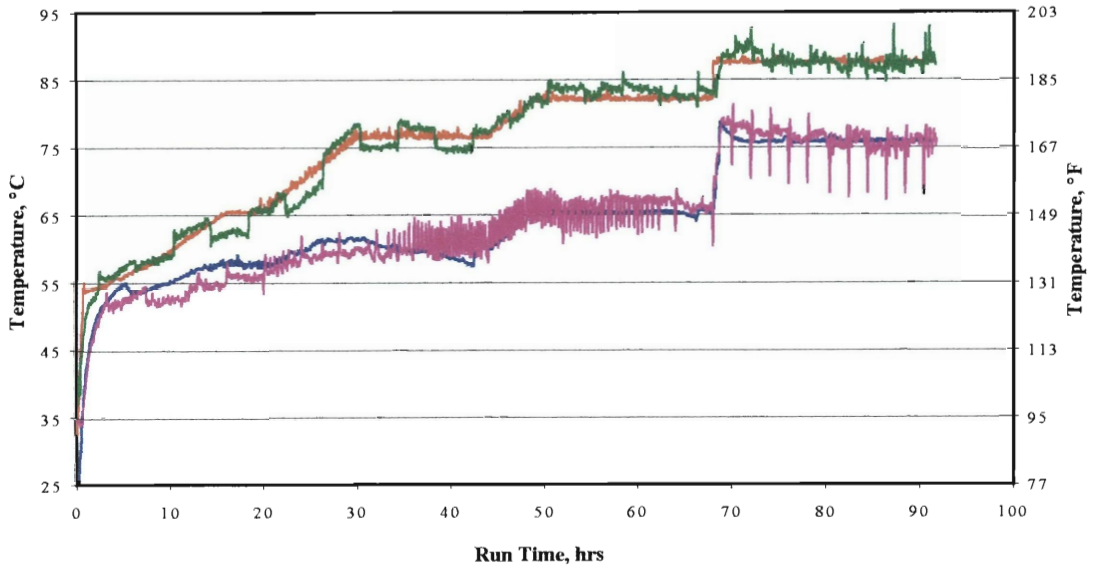
Two hours before the scheduled beginning of the laboratory kiln run the J.U.M. model 3-200 THA (**D**) was turned on and allowed to warm to its set-point temperature (190 °C)and the detector to stabilize. Ice water was added to the mobile condenser unit (**J**). The data acquisition computer (**O**) was started just prior to the schedule beginning. The schedule (**Figure 4.3**) was begun as soon as possible after loading the kiln.

Sampling

Condensate samples from the heat exchanger drain line were collected every four hours during the schedule. The rate of condensate flow as measured by timing how long it took to collect 500 ml in a graduated cylinder. The condensate was combined in 2000-ml Erlenmeyer flasks with ground glass mouth (Jüttner, 1986). The mouth of the flask, including the glass stopper was wrapped in Parafilm M® to ensure the stopper stayed in tight. The sealed flasks were stored in an ice-chilled cooler until organic extraction could be performed.

Placing a Teflon® coil inside a plastic 3-gallon cooler (**J**) created a condenser for the adsorption sampling train. Ice water was added to the cooler to chill the exhaust gas and condense water and less volatile water-soluble organics. The condensate collected in the water trap (**I**) after the condenser coil 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.

A



B

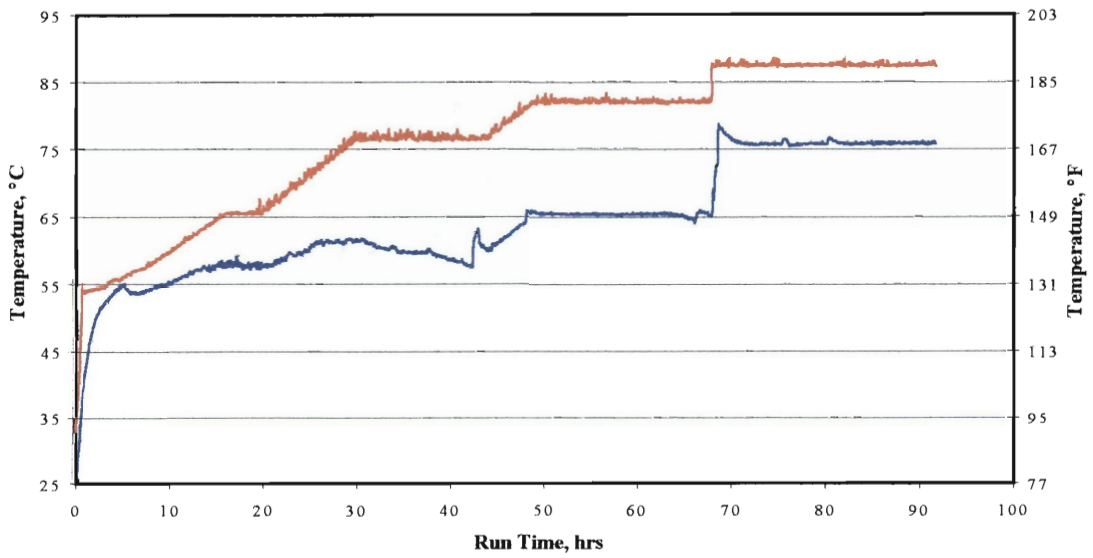


Figure 4.3 Matched drying schedules, laboratory and commercial, ponderosa pine. Diagram **A** shows the schedule for both kilns over lapped. Diagram **B** is a plot of the laboratory schedule. The laboratory kiln shows tighter control of temperatures with less variation. The variation in the laboratory wet-bulb temperature was due to no steam spray being used in the laboratory charges.

Those organic molecules that remained volatile and were not collected in the condensate trap were passed through two Orbo™-32 activated charcoal tubes (Supelco Inc. #2-067) (**G**) in series. Organics adsorbed onto the surface of the "activated" porous structure of the charcoal. Since there is a finite capacity of activated charcoal to adsorb organics (Noyes, 1991), the charcoal was changed every few hours depending upon the concentration of reading of the THA. In the beginning of the schedule the venting/drying rate and hydrocarbon concentration were relatively low so the activated charcoal tubes were not changed often, every 2 hours. As the hydrocarbon concentration in the exhaust increased during the middle of the schedule sampling intervals were shortened to every 30-45 minutes. Later in the schedule the hydrocarbon concentration in the exhaust decreased, thus the sampling interval was again increased to several hours. As each tube was removed from the sampling line, its ends were capped which effectively isolated the charcoal in the glass tube and ensured that no more organics were collected or lost. The sealed tubes were stored in a Ziplock™ plastic bag placed in an ice-chest until organic extraction could be performed.

Grade 5.0 Hydrogen was used for the ionization flame of the THA. The hydrogen regulator was set to 20 psig and the internal regulator of the system metered the gas to the ionization chamber as needed. Grade 5.0 nitrogen was used for the zero gas and purge gas. The second stage of the nitrogen regulator was set to 15 psig and was metered into the ionization chamber to zero the system every few hours through out the experiment. Propane at 885 ppmv in air was specially mixed for this experiment and used to set the span on the THA every few hours. The maximum adjustment required was less than three percent of the reading.

After completion of schedule, the charge was pushed into the covered cooling area where it was broken down. The boards from both charges were processed by a Wagner 683 in-line moisture meter to determine the moisture content at the end of the schedule.

Laboratory Kiln

The laboratory kiln (**Figure 4.4**) had compressed house air (**N**), of known composition, metered into it by a MKS Instruments, Inc. 0-50 liter/minute Type 0558A mass flow meter (**L**), a Type 1559A mass flow controller (**M**), and a direct read flow meter (**Q**). This gave a slightly higher than ambient pressure in the kiln. Flow through the meter was manually controlled with a needle valve as need. The mass flow controller modulated the flow based on a signal from the computer, increasing the flow, as more venting was required. This meter was set to always have a minimum of 4.0 liters/minute flow, slightly more than that being drawn by the THA (3.0 liter/minute) and the adsorption sampling train (0.8 liter/minute).

Twenty-four hours before each laboratory kiln charge, four bundles representing a kiln charge were removed from the freezer and allowed to thaw. Packages remained sealed in plastic to help retain any volatiles. Two hours before the beginning of the kiln run, the support gases (**A**,**B**,**C**) were turned on and the THA (**D**) was turned on and allowed to warm to its set-point temperature (190 °C). Just prior to loading the kiln, the four bundles of 48-inch lumber were unwrapped and each board was trimmed to 44-inches by trimming two inches from each end. This was done so the boards would fit into the kiln and to obtain "fresh" ends, free from any end drying effects that may have occurred during storage. Eight laboratory kiln charges were run. Each charge was two boards wide with ten courses on 0.75 inch stickers (**K**).

The data acquisition/controller computer (**O**) was booted; the specific control files were loaded and initiated. Laboratory kiln conditions were set to closely represent the commercial kiln schedule (**Figure 4.3**). Since the laboratory kiln did not have a heat exchanger the only condensate collected was in the water trap of the adsorption sampling train. The same procedure for collection and storage as detailed for the commercial kiln were followed for this condensate and the activated charcoal tubes (**G**). The THA drew its three liter/minute directly from the kiln, instead of from the exhaust line. The performance of the THA was monitored and adjusted at every sampling interval just as during the commercial charge tests.

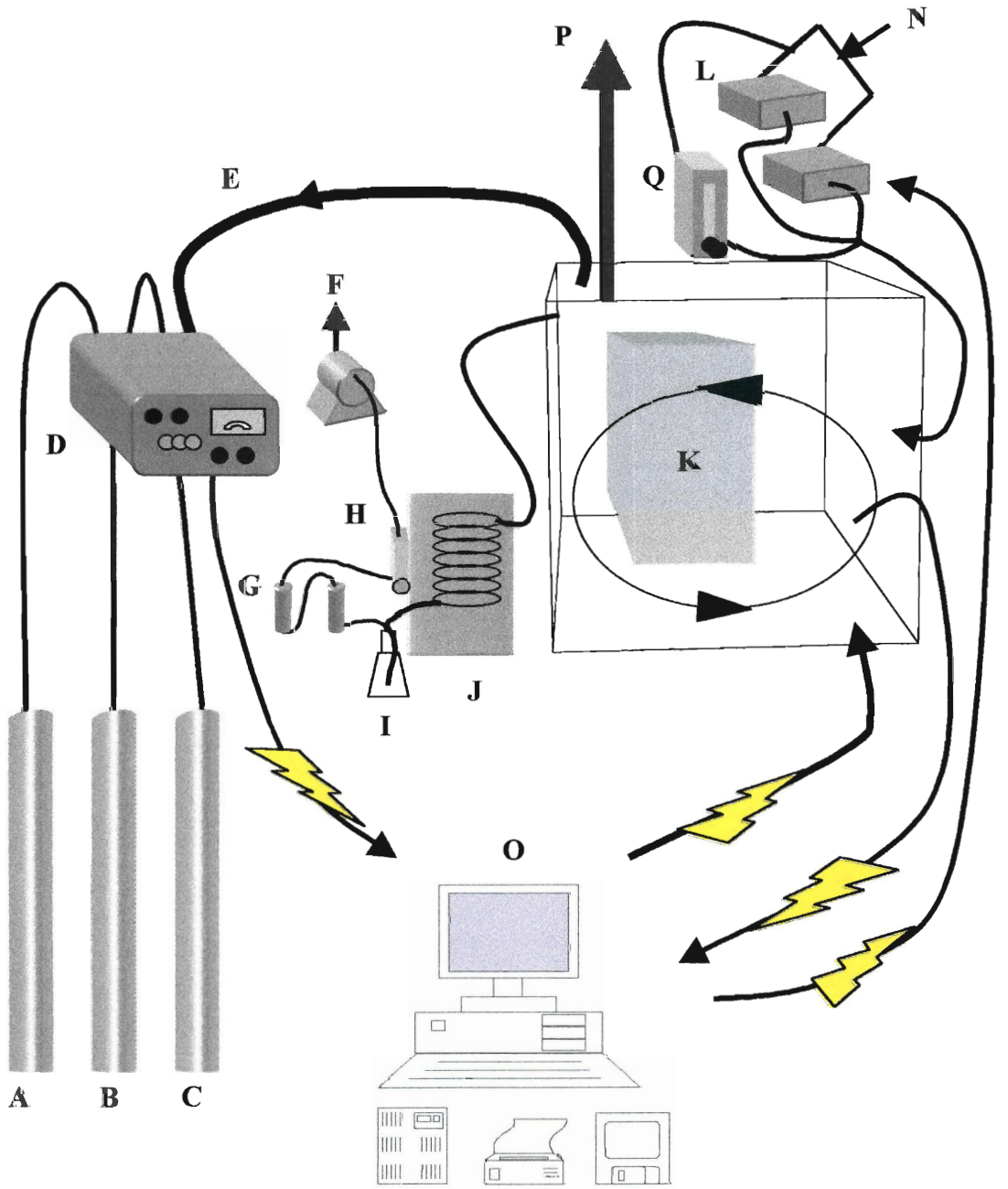


Figure 4.4 Laboratory kiln configuration, ponderosa pine. The charge of lumber (K) inside the kiln which is controlled and monitored by the data acquisition/controller computer (O), D represents the total hydrocarbon analyzer and A,B,C are the support gases. The adsorption sampling train (F,G,H,I,J) was used to collect samples for speciated analysis and the kiln make-up air inlet is represented by L,M,N, and Q.

All sample boards were weighed green, after kiln drying, and 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.

Extraction Procedures

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

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 seal was crimped and the sample was stored below 4 °C (Federal Register, 1995; McDonald & Wastney, 1995, Quigley & Corsi, 1995; USATHAMA, 1990) in a dark environment. Chromatographic analysis was performed within two weeks collection (Bayne et al., 1994; Federal Register, 1995; U.S. EPA, 1994).

The glassware was rinsed between extractions with water, five-ml of HPLC grade methanol and finally five-ml standard dichloromethane solvent solution (Brown, 1971). Between rinsings the separatory funnel drained.

Activated Charcoal Tubes

The activated charcoal was removed from the glass tubes and transferred into correspondingly labeled two-ml plastic Corning® Cryogenic screw top 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 with a Nichiryo repeater pipette set to position 1, with a 60-ml tip.

The vials were sealed with screw caps and placed into a small beaker such that the sample vials remained upright during 15 minutes of sonication. After sonication, the liquid fraction was removed from the vials using a 10-ml glass Micro-Mate® syringe with a 16-gauge metal Luer-lock tip. A non-sterile Millex-FG_{13} 0.2-µm filter was used to ensure the samples were free of particulates. Typically, less than one ml of solvent/sample was collected because some solvent remained wetting the charcoal. This extraction process was repeated and the extractant was combined with the extractant from the first extraction procedure in an auto-sampler crimp seal vial. The Teflon®-lined silicone crimp seals were crimped onto the mouth of the vial and the samples were stored below 4 °C (Federal Register, 1995; McDonald & Wastney, 1995, Quigley & Corsi, 1995; USATHAMA, 1990) in a dark environment until analysis (Bayne et al., 1994; Federal Register, 1995; U.S. EPA, 1994).

GC-MS Analysis

A Hewlett Packard 7673 GC auto-sampler injector manipulating a Hamilton 10uL #80377 syringe (Hamilton Co., Reno Nevada) drew two-µL of sample from each sample vial and injected it through a septa, into the injector port of a Hewlett Packard 5890 Series II Gas Chromatograph. The syringe barrel was thoroughly flushed between sample injections. The split/splitless injector port was controlled to a temperature of 200 °C (392 °F). A split ratio of 1:20 was used to avoid the potentially large solvent tail.

The carrier gas was Grade 4.7 Helium set to a flow rate of 1.02 ml/minute into the 60 meter Supelco 10 column (0.2 mm I.D., phase film 0.2 µm, Catalog # 2-4170 Supelco Bellefonte, PA, USA). The GC oven was programmed to hold at 70 °C for 2 minutes, ramp at 6 °C/minute to 210 °C, then hold for 18 minutes. The separated unknown VOC components moved to a Hewlett Packard 5971 quadrupole mass

selective detector (mass spectrophotometer) set to an ionization energy of 70 eV with the transfer line and ion source set to 280 °C and 180 °C respectively. Identification of the individual components of the samples were determined by retention time and comparison of mass spectra with the NIST/EPA/MSDC 54K Mass Spectral Library and Hewlett Packard MS Chemstation (Catalog #HP G1030A).

Both internal and external standards were used to confirm compound identification and to quantify results. The detector sensitivity to each compound was determined by running a mixture of knowns, making possible accurate quantification of the unknowns. The internal standard was one g/liter undecane added to the dichloromethane (standard dichloromethane solvent solution). The external standards were known concentrations of individual anticipated monoterpenes, and a known mixture of these monoterpenes.

Calculations

The calculation procedure used to determine the dry gas flow rate, moisture content of the wood, hydrocarbon emissions, and monoterpene emissions from the kiln is schematically represented in **Figure 4.5**. Summing the emissions from each time 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 (Yaws, 1977)

$$P_w^0 = \left(\frac{101325\ \text{Pa}}{760\ \text{mmHg}}\right) 10^{16.373 - \frac{2818.6}{T+273.16} - 1.6908 \log(T+273.16) - 0.005754*(T+273.16) + 4.0073*10^{-6}*(T+273.16)^2} \quad (1)$$

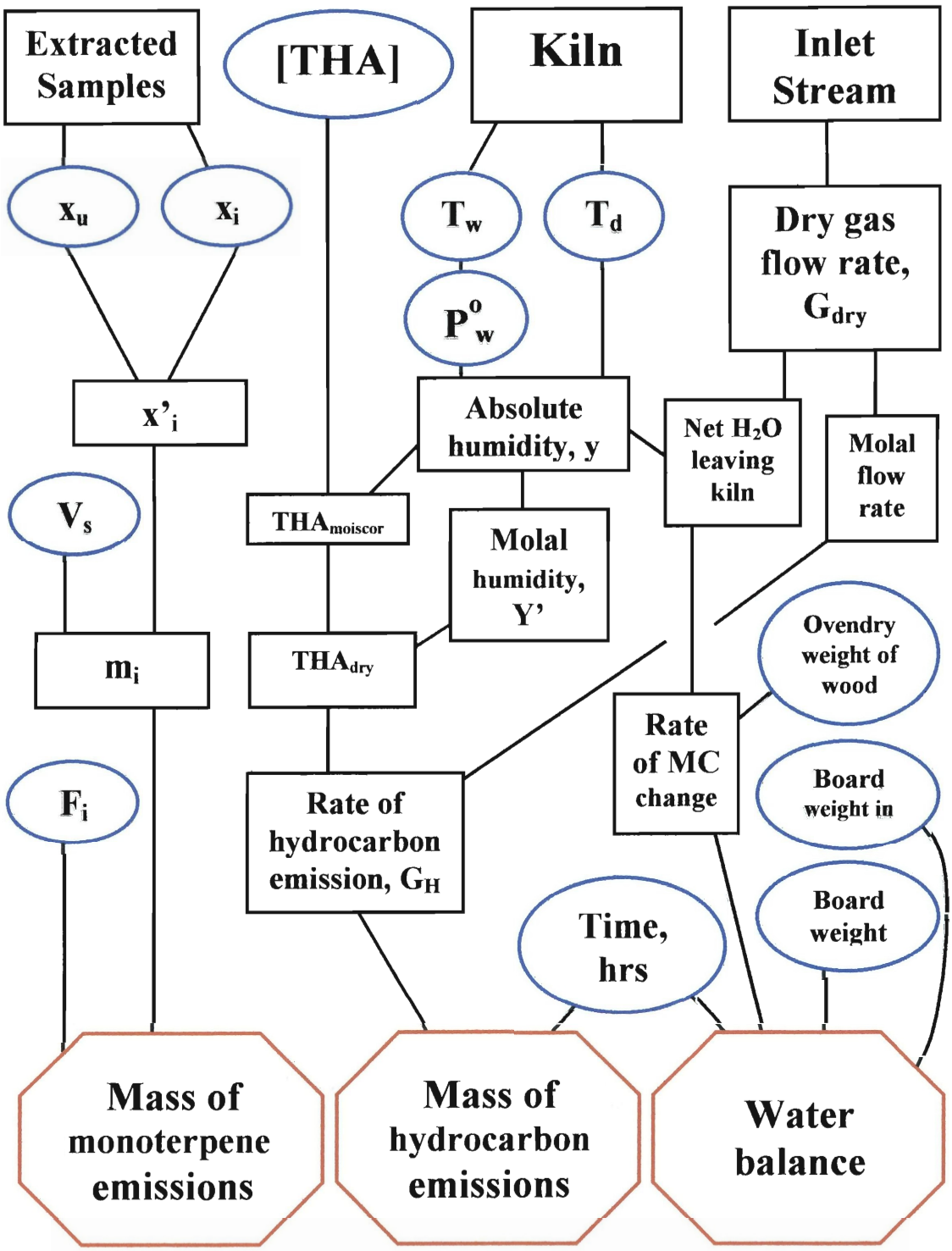


Figure 4.5 Calculation procedure. Measured variables are in ovular shaped fields, calculations and collected samples are in rectangular fields, and the results are in the octagonal fields.

where, T is the wet bulb temperature (°C) inside the kiln. The absolute humidity inside the kiln was calculated as:

$$y = \frac{MW_{water}}{MW_{air}} \frac{1}{\frac{p}{\frac{\Psi_C}{100} * p_w^0} - 1} - \left((T_{DB} - T_{WB}) \left(\frac{h_g / k_y}{\lambda} \right) \right) \quad (2)$$

where p=101,325 Pa, Ψ_C=100%, h_g/k_y=0.95kJ/(kg-K), and λ=2419.3kJ/kg. The molal humidity inside the kiln was calculated as:

$$Y' = \frac{MW_{air}}{MW_{water}} * y \quad (3)$$

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:

$$X_n = X_o - 100 * \frac{\sum_{j=1}^{j=n} G_j * y_j * \Delta t_j}{m_{OD}} \quad (4)$$

Total Hydrocarbon Analysis

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

$$THA_{moiscor} = \left[\frac{THA}{(1 - A)^{E*y+A}} \right] \tag{5}$$

where A = 0.79 and E = -6.649. These values were 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:

$$\mathrm{THA_{dry}} = \mathrm{THA_{moiscor}} * (1 + \mathrm{Y'}) \tag{6}$$

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

$$G_H = (G') \left(\frac{THA_{dry}}{1{,}000{,}000} \right) (MW_{propane}) \left(\frac{1{,}000g}{1kg} \right) \tag{7}$$

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

$$\mathrm{m_H} = \sum_{j=1}^{n} \mathrm{G_{H_j}} * \Delta \mathrm{t_j} \tag{8}$$

where n corresponds to the interval at which the wood moisture content is 12% as determined by equation 4.

Adsorption Sampling Train

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:

$$\mathrm{X'_i} = \frac{1{,}000 \frac{\mathrm{g}}{\ell}}{\mathrm{x_u}} * \mathrm{x_i} \tag{9}$$

where i represents the i^{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.

$$m_i = X'_i * V_s \tag{10}$$

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

$$M_i = \sum_{j=1}^{n} \left(\frac{G'_j}{G'_{CH_j}} \right) * (m_i)_j \tag{11}$$

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

Specific Gravity

The specific gravity (SG) of the laboratory samples was calculated

$$SG = \frac{m_{OD}}{L * W * D * \rho_{H_2O}} \tag{12}$$

where m_{OD} is the weight of the oven dry wood (g), ρ_{H_2O} is the density of water, and length (L), width (W), and thickness (D) are in meters.

Results and Discussion

Wood Properties

Analysis of the packages of lumber used in the laboratory kiln revealed (**Table 4.1**) that the average initial moisture content of the laboratory charges was 125.7%. This calculation is based upon oven dry weights of the samples. The initial moisture content and other properties of the lumber in the commercial kiln were not obtained. Since the laboratory charges were made from the commercial charges using lumber with representative characteristics, the lumber characteristics in the commercial charges is similar to the laboratory charges. It is suspected that the variability in the percentage of heartwood is due to measuring errors because of the consistency in

initial moisture content between matched charges. The number of rings per inch is roughly 9.7 for charges and the average specific gravity of all charges was 0.42.

Table 4.1 Wood properties, ponderosa pine. Physical parameters of the random width ponderosa pine lumber used in the kiln emission study. Emissions, g/kg_{ODwood}, are adjusted to the point when the charged achieved a 12 % moisture content.

Sample Length = 44 inches, Kiln Dry MC 12%							
Charge ID		Green MC %	Heart %	Rings $^{\#}/_{inch}$	Specific Gravity	g Monoterpene $kg_{OD\ Wood}$ @ 12% MC	g THC $kg_{OD\ Wood}$ @ 12% MC
Commercial 1						1.99	3.03
Laboratory	1-20a	120.9	72	6.6	0.41		1.94
	1-20b	120.1	44	11.0	0.41	0.88	
	21-40a	101.1	30	10.9	0.41		1.70
	21-40b	99.68	37	11.8	0.41	1.15	
Commercial 2						2.04	2.60
Laboratory	41-60a	133.9	18	8.6	0.42		2.02
	41-60b	130.2	26	10.0	0.41	0.76	
	61-80a	147.3	4	9.4	0.39		2.21
	61-80b	152.5	16	9.3	0.40		

Water Balance and Suspect Data

The laboratory charges of lumber did not undergo conditioning so the results from the commercial charges were backed-up to a point similar to that obtained in the laboratory kiln. For the commercial charges the moisture content at the point where cool-down began was used, the moisture content was then backed-up three percent. This was done because the charge moisture content was approximately nine percent before conditioning. This schedule time was approximately 92 hours. The cumulative THC quantity at this point was used as the THC emissions for the charge.

There were several problems with equipment during the first four laboratory charges. This was because ponderosa pine required significantly more venting capacity than the species of lumber previously dried in the laboratory kiln. For this reason laboratory results from charges 41-60b and 61-80ba are not reported. The wet-bulb dried out several times during the schedules making accurate analysis impossible. charges 1-20b and 21-40b are suspect due to unexpected THA readings.

The level of emissions may be affected by the initial moisture content of the wood (**Figure 4.6**). A linear regression on the four laboratory charges with total emissions as the dependent variable and initial moisture content as the independent variable produces a slope of 0.0106 (g/kg_{ODwood})/% MC with an r^2 of 0.99. The p-value for this slope is 0.007. Thus, a 20% increase in initial moisture content is likely to result in an emissions increase of 0.21 g/kg_{ODwood}. Although this trend appears clear in the data from the lab, this trend is not reflected in the data from the commercial kiln. The total emissions averaged over the valid laboratory charges, as measured by a THA, were 1.97 g/kg_{ODwood}. Analysis of these lumber charges by adsorption of volatiles with activated charcoal revealed total monoterpene emissions of approximately 0.93 g/kg_{ODwood}. The average total emissions from the commercial kiln were 2.82 g/kg_{ODwood} and 2.02 g/kg_{ODwood} as measured by the THA and adsorption, respectively.

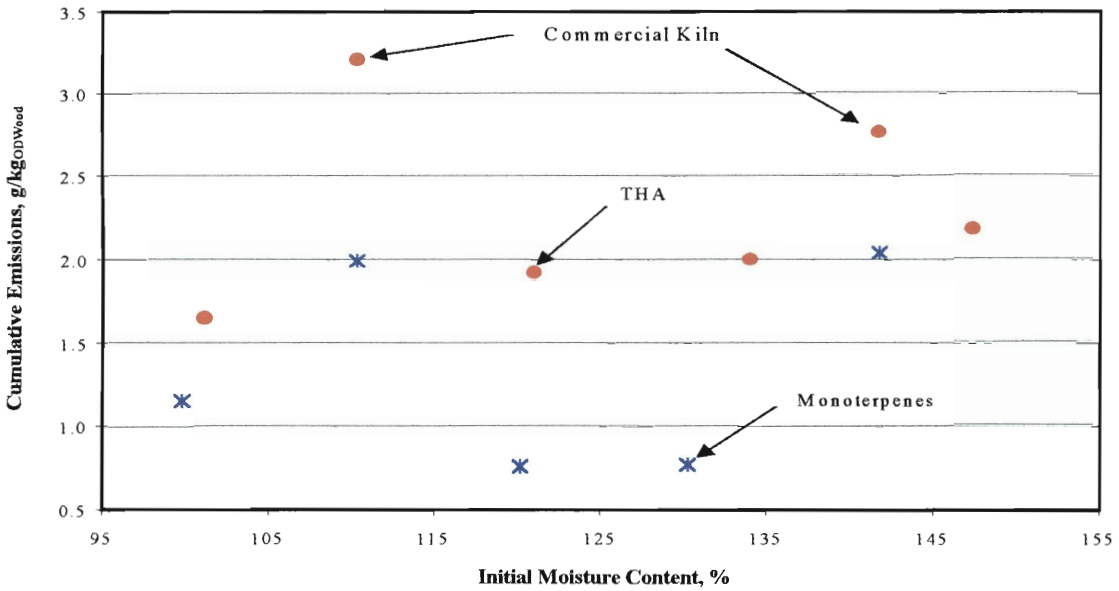


Figure 4.6 Cumulative emissions vs. initial moisture content, ponderosa pine. Cumulative emission, g/kg, from commercial and laboratory charges of ponderosa pine dried to 12% moisture content are reported versus the initial moisture content of the charge.

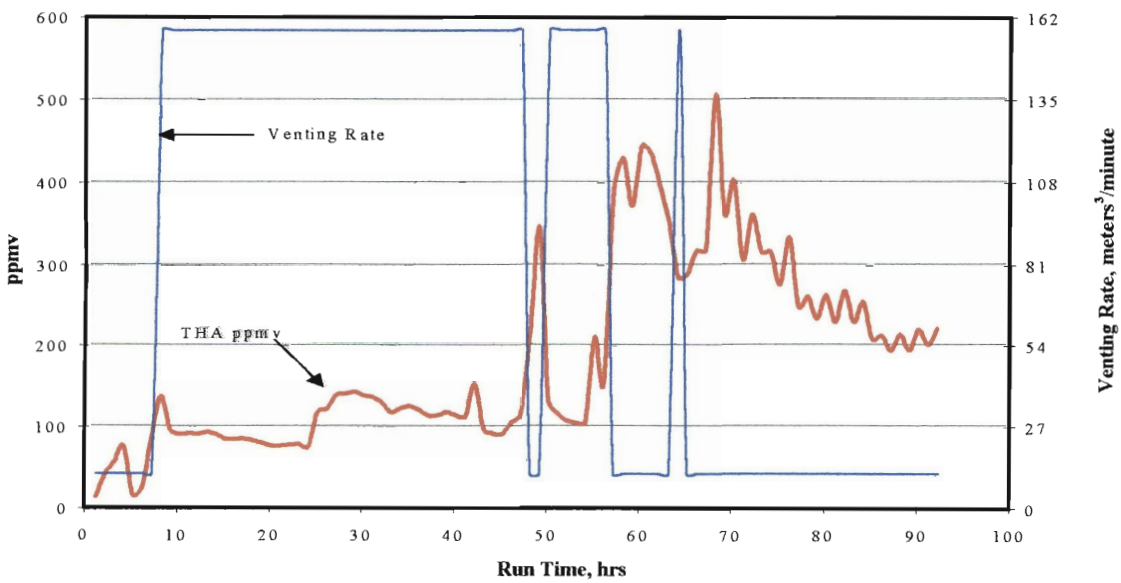


Figure 4.7 Cumulative emissions and venting rate, commercial, ponderosa pine. Cumulative emissions from commercial kiln charge 2, random width ponderosa pine, with THC reported on a dry gas basis in parts per million volumetric basis compared to the venting rate, cubic meters per minute. The venting data was smoothed since the blower was either on or off, which caused many full range spikes in the data.

Commercial Kiln Results

Total Hydrocarbon Analyzer

The hydrocarbon concentration in the exhaust air was relatively low, approximately 100 ppmv, until the 48 hour mark in the schedule (**Figure 4.7**). This is likely due to the high volume of venting occurring during this time. When there is a drop in venting rate at hour 49, the concentration of emissions in the exhaust spikes. At hour 50, when venting volume increases again, the concentration of emissions falls back to 100 ppmv. At hour 57 venting stops and the concentration of hydrocarbons spikes to 840 ppmv. Venting, for the remainder of the schedule is relatively low allowing the concentration of hydrocarbons to remain relatively high for the remainder of the schedule.

The hydrocarbon concentration in the exhaust reacts inversely to the venting rate from the kiln. Every time the venting rate dropped the concentration of hydrocarbons in the exhaust spiked. After venting began at the six-hour point in the schedule, the hydrocarbon concentration remained relatively low.

After hour 60 the emissions rate decreased, rapidly as indicated by a change in the slope of the cumulative emissions curve (**Figure 4.8**). For the remainder of the drying schedule the emissions rate decreased slowly. The total quantity of hydrocarbons released averaged 2.82 g/kg_{ODwood} (5.20 lbs/mbf nominal) for the two commercial kiln charges. The total emissions values for each of the two commercial kiln charges are within 16% of each other. It is not known if the difference is due to actual variability of the VOCs released or sampling error. This measured ratio of emissions is three times the value reported for ponderosa pine by NCASI (1.00 g/kg_{ODwood}).

After hour 30 the moisture content of the wood decreased rapidly in almost a linear fashion (**Figure 4.8**). When cumulative emissions are plotted as a function of moisture content (**Figure 4.9**), the quantity of emissions released is not proportional to the change in moisture content as seen in chapter III for the Douglas-fir.

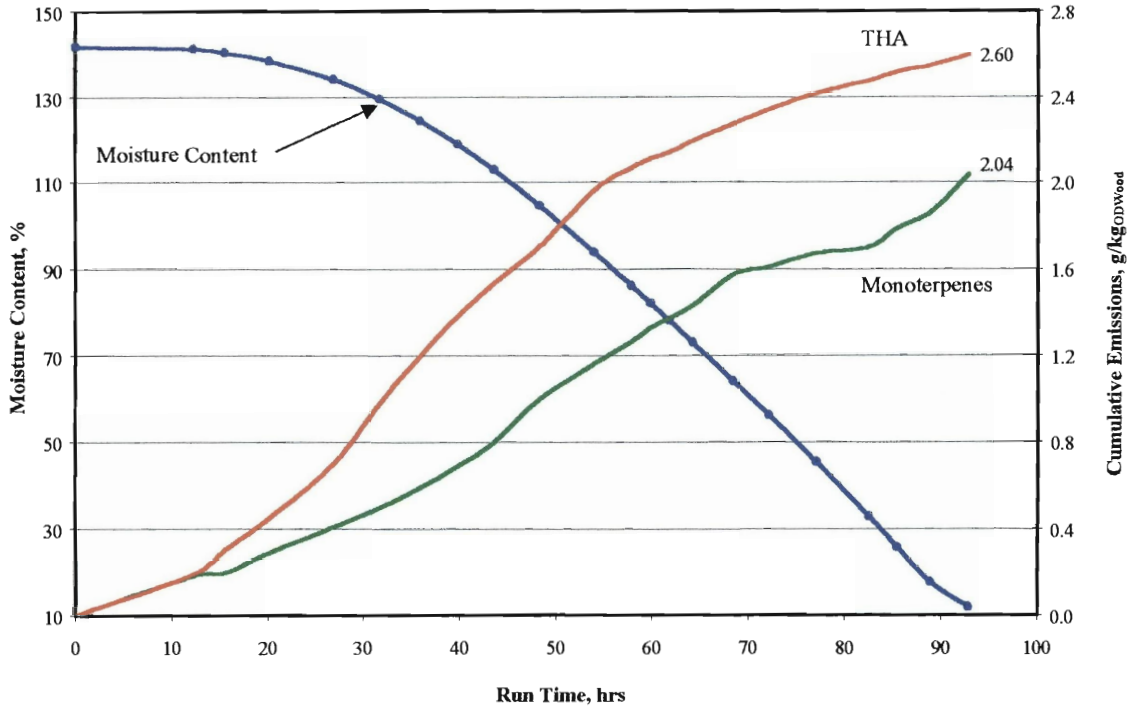


Figure 4.8 Cumulative emissions and charge moisture content, ponderosa pine. Commercial charge 2, random width ponderosa pine, dried to 12% moisture content and the moisture content of the charge.

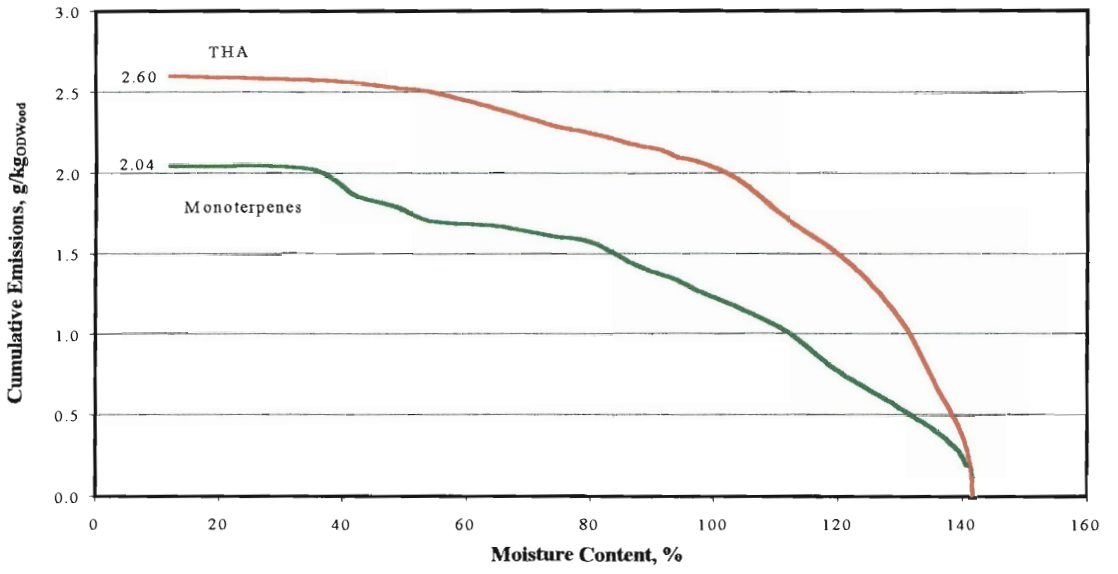


Figure 4.9 Cumulative emissions vs. moisture content, commercial, ponderosa pine. THC from commercial charge 2 compared to moisture content of the random width ponderosa pine.

Monoterpenes

Speciated information for commercial kiln charges indicates that β-myrcene and Δ-3-carene are the dominantly emitted monoterpenes (**Figure 4.10).** 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 pine veneer drier exhaust are similar to that observed for the lumber dry kiln, with β-myrcene and Δ-3-carene being detected in concentrations several times greater than the other monoterpenes (Cronn et al., 1983). The rate of monoterpene emissions gradually increases during the drying schedule. This trend mirrors the tend seen for total hydrocarbons as measured by the THA. The relative ratio of detected monoterpenes is similar between commercial kiln runs one and two as was the total quantity of monoterpenes detected. The total detected for run one was 1.99 g/kg_{ODwood}, where as in run two 2.04 g/kg_{ODwood} was collected.

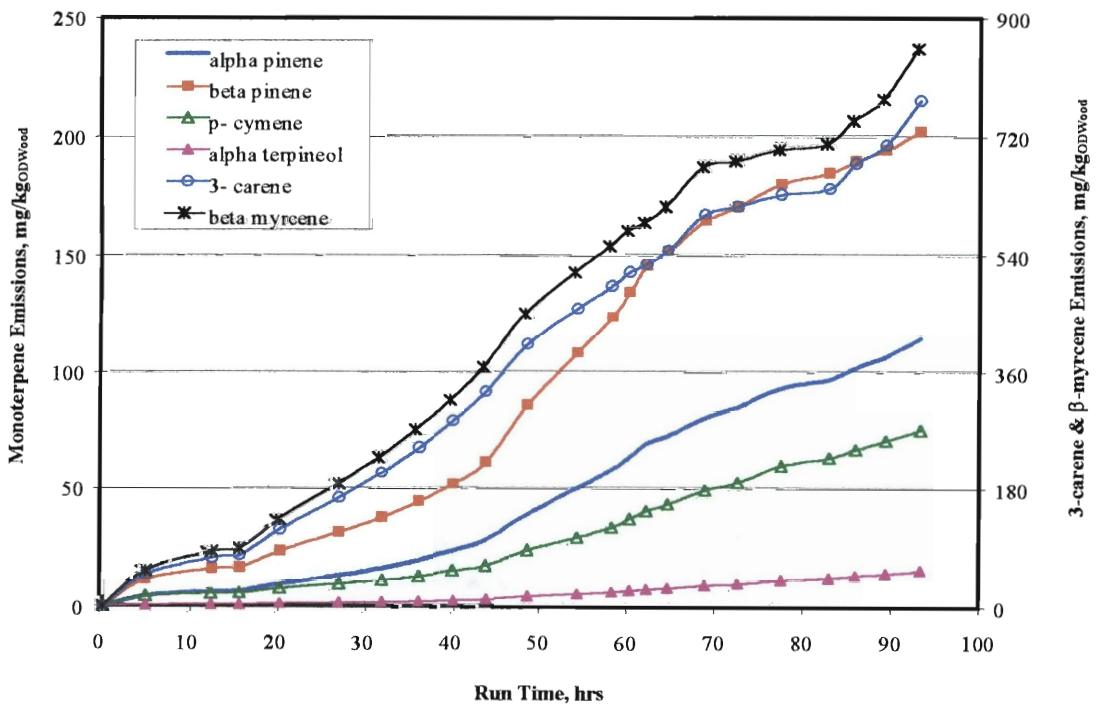


Figure 4.10 Cumulative speciated monoterpene emissions, commercial, ponderosa pine. Commercial charge 2, dried to 12% moisture content.

Heat Exchanger Condensate

There were only two monoterpenes identified in the condensate from the heat exchanger, α-terpineol (0.047 mg/kg_{ODwood}) and 4-terpineol (0.119 mg/kg_{ODwood}). A total of 1,185 liters of water was calculated to be condensed in the heat exchanger and approximately 0.166 mg/kg_{ODwood} of monoterpenes. α-terpineol is slightly soluble in water. The only other monoterpene, of those detected in the exhaust stream, which is also soluble in water is α-pinene. However, the boiling point of α-pinene is 156.2 °C as compared to 217.5 °C for α-terpineol. The temperature of the condensate leaving the heat exchanger was 44 °C. It is likely that this temperature was high enough to volatilize a significantly larger portion of the α-pinene such that it was undetected.

Lab Results

Total Hydrocarbon Analyzer

The venting rate and hydrocarbon concentration in the laboratory kiln (**Figure 4.11**) affect the total VOC emissions (**Figure 4.12**) in a similar manner as in the commercial kiln (**Figures 4.8** and **4.9**).

The hydrocarbon concentration in the exhaust air increased rapidly from near zero to 1311 ppmv at approximately six hours into the schedule when venting began (**Figure 4.11**). The hydrocarbon concentration in the kiln likely increased over this six-hour time interval due to the kiln not venting.

After venting began at the six-hour point in the schedule, the hydrocarbon concentration rapidly decreased. The venting rate plataued between hours 10 and 36 of the schedule (**Figure 4.11**), resulting in an emissions rate that was almost constant from hour eight to hour 36 of the schedule. This is demonstrated by the linear part of the cumulative emissions curve in **Figure 4.12**.

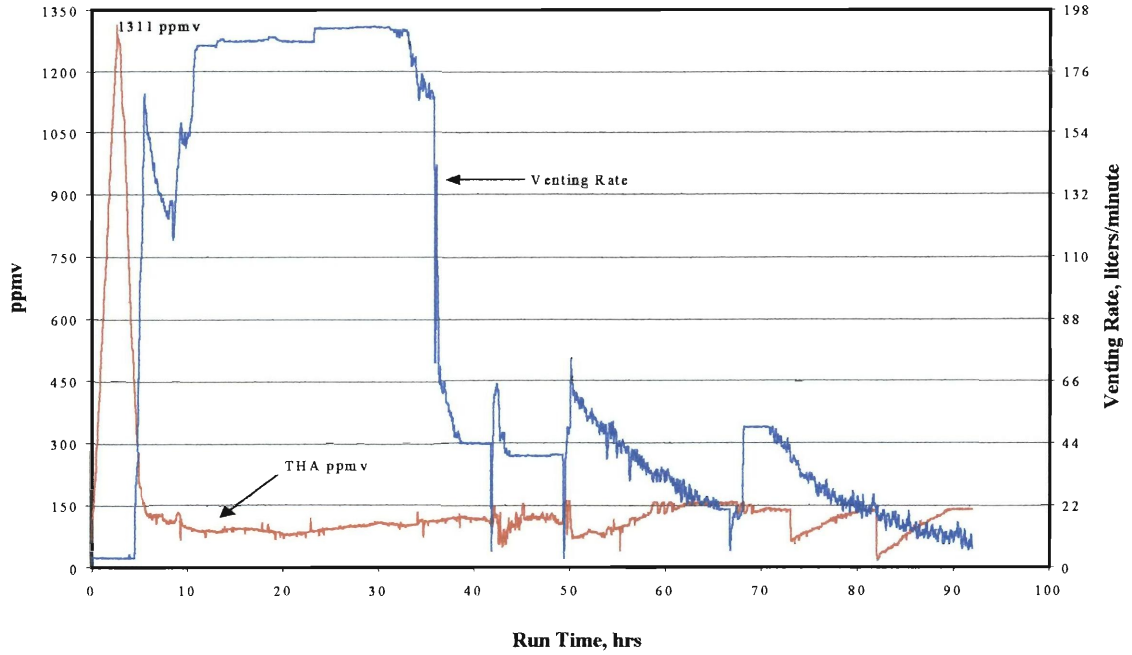


Figure 4.11 Cumulative emissions and venting rate, laboratory, ponderosa pine. Emissions, from random width ponderosa pine, reported on a dry gas basis in parts per million volumetric basis compared to the venting dry gas flow rate, liters/minute.

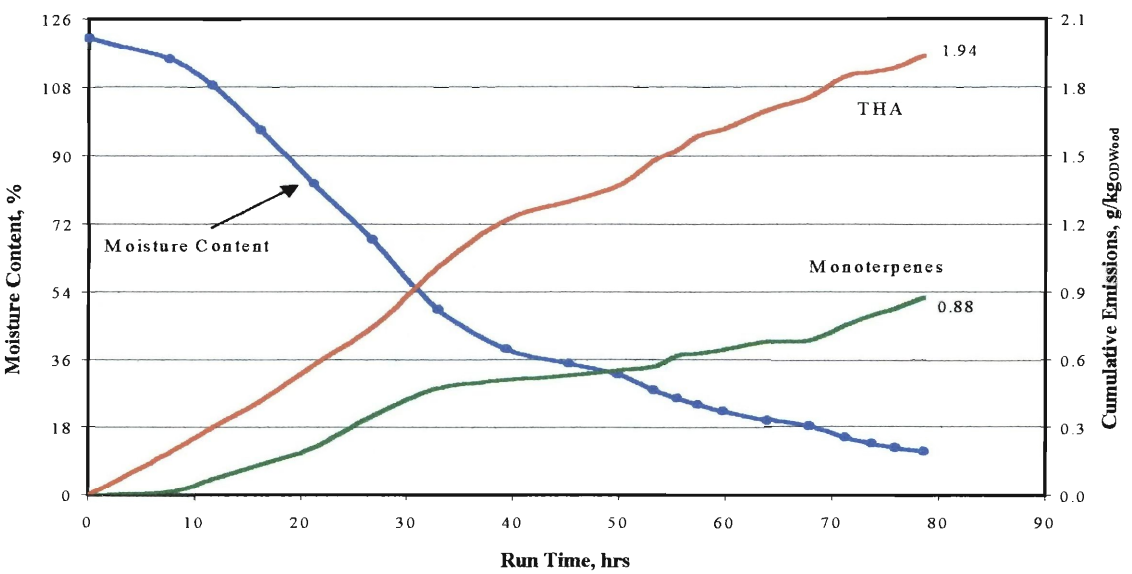


Figure 4.12 Cumulative emissions and charge moisture content, ponderosa pine. Emissions from laboratory charge 1-20a and b, random width ponderosa pine, dried to 12% moisture content, compared to the moisture content of the charge.

Between hours 36 and 43 the emissions rate decreased, as indicated by the knee in the cumulative emissions curve (**Figure 4.12**). For the remainder of the drying schedule the emissions rate was constant as demonstrated by the second linear portion of the cumulative emissions curve in **Figure 4.12**.

The total quantity of hydrocarbon emissions averaged 1.97 g/kg_{ODwood}, with a standard deviation of 0.21 g/kg_{ODwood}, for the four laboratory kiln charges. Results indicate, with 95% confidence, that the laboratory kiln, drying random width ponderosa pine, will emit between 1.76 g/kg_{ODwood} and 2.18 g/kg_{ODwood} of total hydrocarbon.

The difference in emissions among the laboratory charges may be due to actual variability in initial moisture content. This ratio of emissions is approximately twice the value reported for ponderosa pine by NCASI (1.00 g/kg_{ODwood}). Cumulative total hydrocarbon emissions increased in a linear fashion from a charge moisture content of 100% to the final MC (**Figure 4.13**). There was a slightly increased rate of emissions from the initial moisture content to about 100%.

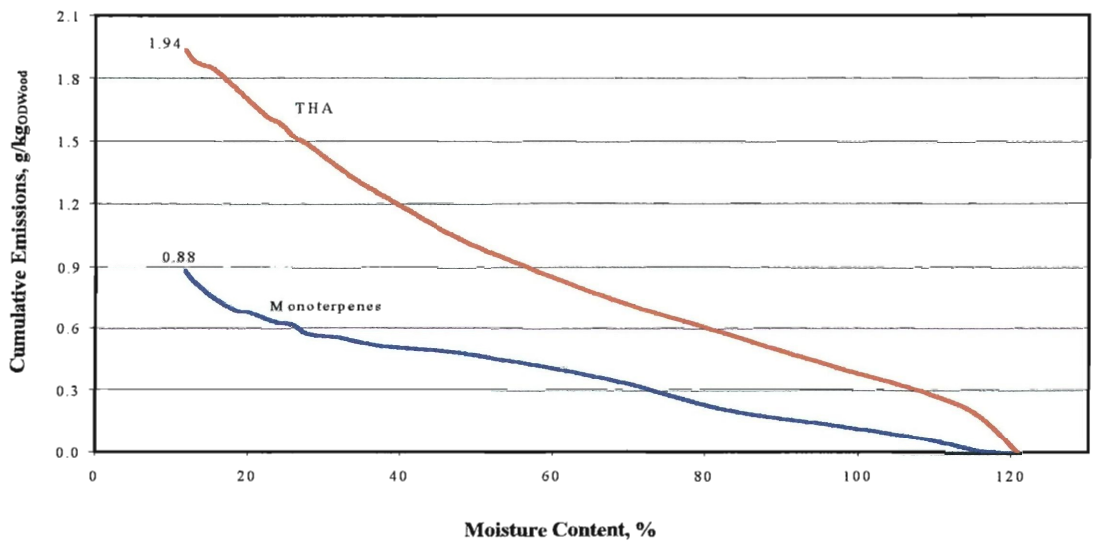


Figure 4.13 Cumulative emissions vs. moisture content, ponderosa pine. Emissions from laboratory charge 1-20a and b compared to the random width ponderosa pine charge moisture content.

Below 100% moisture content the rate was linear. This trend is similar to that observed for Douglas-fir in both the commercial and laboratory kilns (Chapter III). However, the trend is different from that observed in the commercial kiln for ponderosa pine. Even though many of the volatile compounds released from ponderosa pine as it dries are not soluble in water it is possible that they may move to the surface of the drying lumber 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

GC-MS analysis of the kiln exhaust samples identified β-myrcene and Δ-3-carene as the dominantly emitted monoterpene species (**Figure 4.14**). This is the same trend shown in the commercial kiln study and in the literature. The relative ratios of each of the monoterpenes emitted are similar between laboratory charges. β-myrcene and Δ-3-carene is the dominant species emitted, showing emissions an order of magnitude greater than the next most abundant emittant, β-pinene.

Comparisons Between Commercial and Laboratory Kiln

The laboratory kiln performed like a scaled down version of the commercial lumber dry kiln in some respects and not others. Venting versus time in each kiln follows a very similar pattern, as shown in **Figures 4.7** and **4.11**. In addition the rate of total hydrocarbon emissions begins to decrease at approximately 60 hours in both kilns. When emissions are plotted against moisture content (**Figures 4.9**, **4.13**, and **4.15**) the profiles show different shapes. The commercial kiln (**Figure 4.9** and **4.15**) had a high rate of emissions from the beginning of the schedule until the charge

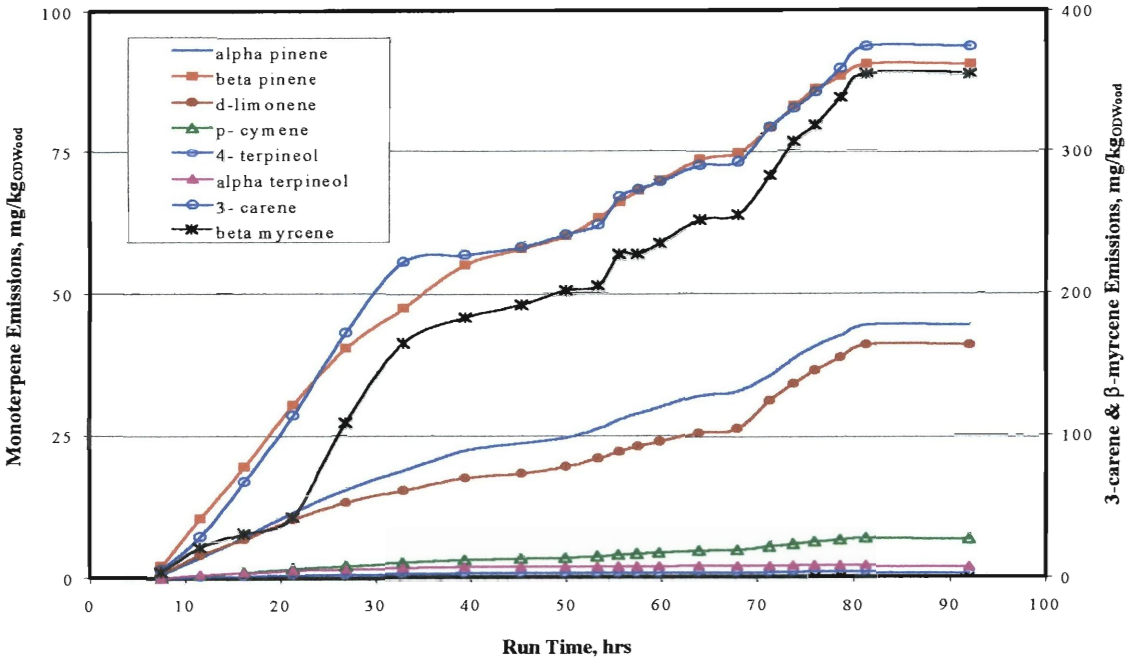


Figure 4.14 Cumulative speciated monoterpene emissions, laboratory, ponderosa pine. Emissions form laboratory charge 1-20b dried to 12% moisture content.

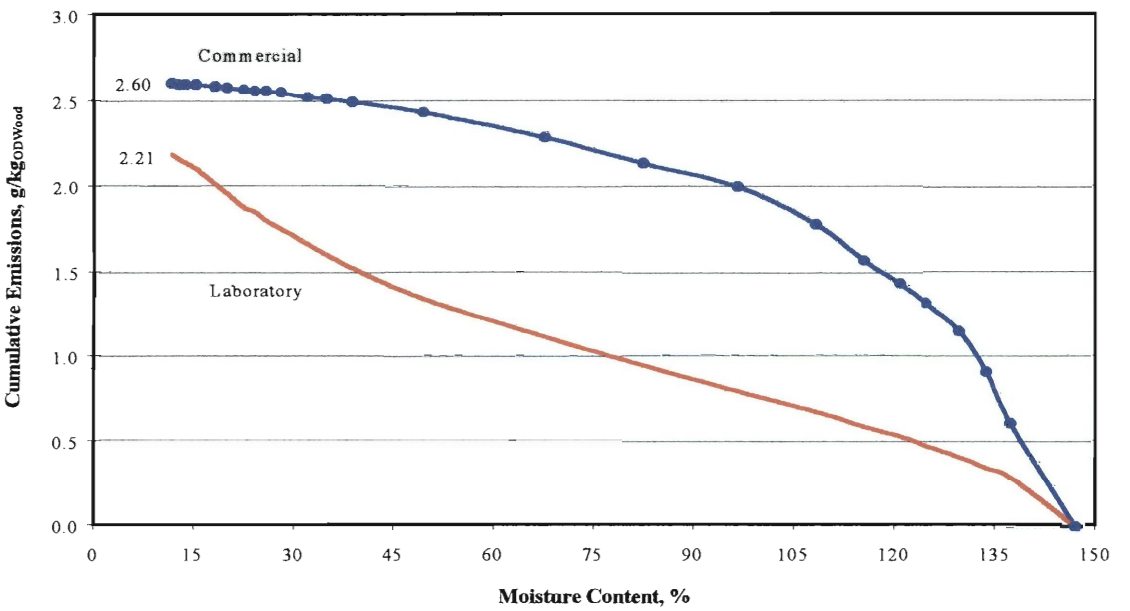


Figure 4.15 Cumulative emissions, laboratory and commercial kilns. Laboratory charge 61-80a and commercial charge 2.

achieves approximately 100% MC then the rate of emissions gradually slows. The laboratory kiln had relatively linear emissions from the beginning of the schedule until the end (**Figure 4.13** and **4.15**) with a slight increase below 45% moisture content.

The THC emissions released averaged 1.97 g/kg_{ODwood} from the laboratory kiln and 2.82 g/kg_{ODwood} from the commercial kiln. A two-tailed p-value from a t-test attempting to show a difference between the population means of the laboratory and commercial kiln total emissions is 0.027. This p-value suggests that it is possible that the two population means are different. Additional replicates may help to strengthen or refute this model but in environmental field sampling, where agreement of between 10 and 20% is considered good, these values are not similar enough to claim the laboratory kiln is representative of the commercial kiln. Even so, results from the GC-MS analyzer indicated that the monoterpene emissions from each kiln were emitted in similar ratios, if not in similar total quantities.

Even though there is evidence; venting profiles vs. time, emission profiles vs. time, emission profiles vs. moisture content, and monoterpene species ratios all indicate that the laboratory kiln is an effective tool in predicting emissions from larger kilns. The fact that the total quantity of hydrocarbon emissions measured in the laboratory kiln was 30% less than the commercial kiln, refutes any comparisons between the two. 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.

Conclusions

Total emissions released from both the laboratory and commercial kiln charges were monitored. Analysis of the emissions revealed approximately 1.97 and 2.82 g VOC / kg oven dry random width ponderosa pine from the laboratory and commercial kilns, respectively. It is not known if the laboratory kiln can be used to accurately predict total emissions from a commercial kiln without having to use an adjustment

factor due to potential loss of hydrocarbons during sample transportation to the laboratory.

Analysis of speciated emissions revealed that qualitative comparison between the commercial kiln and laboratory kiln may be valid. The relative ratios of monoterpenes are the same for both kilns. The total monoterpene emissions detected are similar to the total amount detected with THA analysis.

The results from this study should affect the forest products industries thinking on Title V (permit acquisition) issues because the emissions reported in this thesis are two to three times higher than previously reported values. This study was able to determine the expected quantity of emissions, or a range of emissions to expect when drying random width ponderosa pine with a standard commercial schedule. Accurate determinations of expected emission quantities would enable more precise matching of permits to actual emissions quantities.

CHAPTER V Conclusions

Adsorption and condensation of monoterpenes was successfully conducted on the humid venting exhaust from a laboratory lumber dry kiln. The condensation/adsorption method employed to collect samples for speciated analysis does not account for all the volatile compounds in the exhaust from a lumber dry kiln drying Douglas-fir. THC analysis, using a THA, reported five times more volatiles in the exhaust from a kiln drying Douglas-fir. Condensation and adsorption of volatiles with subsequent organic extraction appears to produce samples representative of the THC emissions in that the shapes of the total hydrocarbon emission curves have a similar shape, only different magnitudes.

The second phase of this thesis, monitoring and comparing THA measured THC emissions from matched laboratory and commercial kiln charges of 2x6 Douglas-fir, revealed approximately 1.0 g THC / kg_{ODwood} from both kilns. This indicates that the laboratory kiln can be used to accurately predict total emissions from a commercial kiln without having to use an adjustment factor.

GC-MS analysis of adsorbed emissions revealed that qualitative and quantitative comparisons between the commercial kiln and laboratory kiln are valid. The relative ratios of monoterpenes were the same for both kilns. However, the monoterpene emissions detected were one-fifth those detected with THA analysis. α-pinene was detected in quantities ten times greater than the other monoterpenes, with β-pinene and d-limonene being the next most abundant. The smaller quantity of THC emissions detected by analyzing for monoterpenes alone is likely due to a large percentage of non-monoterpene compounds in the gas stream which are not detected.

The third phase of this thesis, monitoring and comparing THA measured THC emissions from matched laboratory and commercial kiln charges of random width ponderosa pine, revealed an average emissions of 2.25 g THC / kg_{ODwood}. The average THC emissions from the commercial kiln were 2.82 g/kg_{ODwood} as compared to 1.97 g/kg_{ODwood} for the laboratory kiln.

GC-MS analysis of exhaust samples revealed that qualitative comparison between the commercial kiln and laboratory kiln may be valid. The relative ratios of monoterpenes were the same for both kilns. The total monoterpene emissions detected were similar to the amount detected with THA analysis. Δ-3-carene and β-myrcene were emitted in quantities three times greater than α-pinene β-pinene and d-limonene. The total monoterpene emissions detected were similar to the THC detected with the THA. This is likely due to a relatively high concentration of condensation polymers of isoprene in ponderosa pine.

Further research is needed to compare condensation and adsorption with the use of a THA. Studies measuring the other volatiles in kiln exhaust may give new insights into the true relationship between the THC detected from adsorption and the use of a THA.

The results from this thesis should affect the forest products industries thinking on Title V (permit acquisition) issues. This study was able to determine the expected quantity of emissions, or a range of emissions to expect when drying 2x6 Douglas-fir and random width ponderosa pine, with a standard commercial schedule. Accurate determinations of expected emission quantities would enable more precise matching of permits to actual emissions quantities.

The use of this laboratory model is much more efficient than monitoring commercial kiln emissions because of its location, size of lumber charge, and proximity to laboratory analysis equipment. The small size of the lumber charge makes it possible to economically test various schedules quickly and to compare emission rates.

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APPENDICES

APPENDIX A Douglas-fir data

Commercial Charge 1, 2x6 Douglas-fir, June 3, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC*	g / kg_{ODwood} THC*	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	d-limonene	p-cymene	4-terpineol	α-terpineol
5.5	56.0	178.4	164.9	7.8	0.0	0.0	0.0	0.26	0.11	41.81	3.13	0.28	1.30	0.26	0.01	0.01
6.4	55.1	176.8	172.0	33.7	1312.8	2.8	0.0	0.32	0.16	44.62	2.56	0.57	1.63	0.43	0.01	0.01
7.3	54.7	178.8	173.9	22.3	360.3	3.7	0.1	0.36	0.18	16.68	0.88	0.07	0.42	0.12	0.00	0.00
8.3	54.5	179.5	174.1	7.8	70.4	3.8	0.1	0.41	0.18	4.95	0.27	0.04	0.13	0.04	0.00	0.00
9.3	54.1	180.5	174.0	7.8	0.8	3.8	0.1	0.45	0.20	12.61	0.62	0.05	0.32	0.11	0.01	0.01
10.8	53.0	180.1	172.8	37.9	0.8	3.8	0.1	0.48	0.21	13.35	0.73	0.13	0.45	0.17	0.02	0.02
12.4	51.4	180.2	171.7	71.5	4.2	3.9	0.1	0.50	0.24	20.78	0.79	0.08	0.58	0.22	0.03	0.03
15.4	46.5	179.1	166.0	97.1	0.0	3.9	0.1	0.54	0.28	20.08	0.57	0.12	0.55	0.22	0.02	0.01
17.4	42.5	177.5	160.5	108.2	0.8	3.9	0.1	0.54	0.30	19.76	0.61	0.12	0.57	0.24	0.02	0.03
19.3	38.4	178.4	159.9	121.3	0.0	4.0	0.1	0.54	0.31	6.35	0.27	0.08	0.33	0.14	0.01	0.02
21.5	33.5	177.4	159.1	130.4	0.2	4.0	0.1	0.54	0.32	3.58	0.18	0.05	0.22	0.10	0.02	0.03
23.5	29.0	177.0	155.9	138.7	2.9	4.1	0.1	0.55	0.32	0.96	0.04	0.00	0.04	0.02	0.01	0.02
25.7	24.4	181.4	154.6	132.6	208.8	7.8	0.1	0.55	0.33	7.26	0.31	0.09	0.36	0.15	0.00	0.00
36.7	17.4	177.0	156.8	7.8	2.1	12.6	0.2	0.65	0.37	7.74	0.16	0.04	0.36	0.13	0.00	0.00
40.8	16.4	178.4	158.7	7.8	0.7	12.6	0.2	0.66	0.38	7.36	0.16	0.04	0.39	0.14	0.01	0.01
49.1	15.0	177.8	165.6	7.8	0.0	13.3	0.2	0.72	0.39	4.69	0.09	0.02	0.23	0.08	0.00	0.00
56.9	14.0	179.9	164.2	7.8	0.2	13.3	0.2	0.79	0.40	4.84	0.15	0.04	0.56	0.15	0.00	0.00
62.9	13.3	180.6	161.8	7.8	0.4	13.3	0.2	0.82	0.40	1.79	0.14	0.05	0.68	0.18	0.01	0.01
75.5	8.0	82.2	65.5	6.4	250.3	13.4	0.4	0.82	0.43	4.00	0.09	0.03	0.36	0.12	0.01	0.01
Total Condenstate										0.72	0.04	0.01	0.03	0.01	0.14	0.29

* THC data is not accurate because of problems with the detector during this kiln schedule.

Commercial Charge 2, 2x6 Douglas-fir, July 23, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC	g / kg_{ODwood} THC	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	d-limonene	p-cymene	4-terpineol	α-terpineol
3.5	62.3	170.6	154.0	7.8	78.9	0.0	0.0	0.03	0.01	5.24	1.01	1.02	2.04	0.46	0.04	0.03
6.0	62.0	179.2	166.2	40.8	2780.1	0.9	0.0	0.03	0.02	4.31	1.05	0.08	0.52	0.18	0.02	0.01
6.7	61.1	178.1	164.6	49.6	2280.9	6.6	0.1	0.03	0.05	20.99	5.07	0.44	1.64	1.46	0.08	0.05
7.2	60.6	178.2	164.6	22.3	1801.6	9.2	0.2	0.03	0.06	8.01	0.65	0.11	0.26	0.16	0.03	0.02
7.7	60.5	178.6	164.6	7.8	1688.9	9.9	0.2	0.03	0.06	1.31	0.07	0.01	0.04	0.02	0.01	0.01
8.2	60.3	178.6	164.8	7.8	1670.1	10.6	0.2	0.04	0.06	1.69	0.12	0.02	0.05	0.03	0.01	0.01
8.7	60.1	178.7	165.0	22.4	1195.8	11.5	0.2	0.04	0.06	2.85	0.23	0.02	0.10	0.06	0.02	0.01
9.2	60.0	178.6	164.8	7.8	1038.5	11.9	0.2	0.04	0.07	2.09	0.20	0.02	0.09	0.05	0.01	0.01
10.0	59.6	179.5	165.2	46.5	881.1	13.1	0.2	0.04	0.07	3.29	0.25	0.02	0.13	0.07	0.01	0.01
10.8	58.6	179.4	164.7	37.2	755.8	15.3	0.3	0.04	0.08	7.95	0.71	0.07	0.38	0.23	0.04	0.04
12.4	56.6	178.1	162.7	63.0	558.7	19.4	0.3	0.05	0.09	8.70	0.65	0.08	0.40	0.25	0.04	0.03
14.1	53.5	178.2	162.1	84.7	472.0	24.2	0.4	0.05	0.11	13.39	1.07	0.13	0.74	0.47	0.06	0.05
17.1	46.9	177.4	159.5	100.9	354.7	32.3	0.6	0.05	0.12	13.66	0.82	0.13	0.72	0.45	0.05	0.04
20.1	39.7	177.4	156.9	114.8	264.5	39.6	0.7	0.05	0.14	16.17	0.82	0.14	0.79	0.49	0.06	0.05
26.6	25.2	174.7	148.1	68.5	217.9	52.0	0.9	0.05	0.18	14.68	0.64	0.12	0.71	0.43	0.09	0.07
29.6	22.0	174.9	147.7	48.2	225.0	55.1	0.9	0.06	0.19	8.35	0.37	0.07	0.40	0.24	0.05	0.04
38.6	18.8	175.3	150.1	7.8	230.0	58.7	1.0	0.07	0.20	3.77	0.20	0.05	0.39	0.23	0.01	0.01
43.7	17.6	175.7	150.2	22.7	268.0	60.1	1.0	0.08	0.20	2.84	0.19	0.07	1.00	0.36	0.02	0.01
48.8	16.7	177.6	149.5	7.8	251.1	61.3	1.1	0.09	0.21	2.30	0.15	0.06	0.82	0.29	0.01	0.01
54.8	15.7	178.2	152.4	7.8	361.1	62.7	1.1	0.09	0.21	2.00	0.13	0.05	0.71	0.25	0.01	0.01
61.1	14.7	179.5	151.6	7.8	341.0	64.1	1.1	0.09	0.21	1.42	0.09	0.04	0.50	0.18	0.01	0.01
79.9	12.9	179.9	151.8	7.8	216.7	66.1	1.2	0.09	0.21	1.05	0.07	0.03	0.37	0.13	0.01	0.01
Total Condenstate										1.6	0.1	0.0	0.06	0.02	0.30	0.63

Laboratory Charge 1, 2x6 Douglas-fir, July 11, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC	g / kg_{ODwood} THC	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	d-limonene	p-cymene	4-terpineol	α-terpineol
1.5	60.5	61.5	52.8	0.5	319.9	0.0	0.0	0.02	0.00	0.24	0.02	0.00	0.01	0.00	0.00	0.00
3.3	59.0	82.4	76.8	47.2	2517.5	7.4	0.1	0.04	0.03	21.46	2.17	0.17	1.28	0.26	0.04	0.04
4.1	57.5	81.8	77.0	46.8	2032.6	15.7	0.2	0.05	0.06	26.11	2.62	0.22	1.49	0.33	0.18	0.22
4.9	56.8	82.5	77.4	46.9	1463.9	19.3	0.3	0.06	0.08	21.05	1.81	0.16	1.09	0.26	0.17	0.25
5.7	54.2	82.0	76.9	46.8	1044.0	23.6	0.3	0.07	0.10	15.64	1.09	0.10	0.72	0.18	0.15	0.23
6.7	52.0	82.7	76.9	47.2	444.9	27.4	0.4	0.07	0.12	17.23	1.23	0.11	0.85	0.22	0.26	0.46
8.1	50.4	82.1	77.2	47.3	2135.5	32.3	0.5	0.08	0.14	14.96	0.94	0.08	0.68	0.20	0.27	0.53
9.7	48.9	82.6	76.4	49.5	468.5	38.4	0.6	0.09	0.16	12.66	0.62	0.06	0.51	0.16	0.21	0.46
11.3	46.7	82.4	76.1	47.4	229.1	42.1	0.6	0.09	0.17	13.00	0.64	0.07	0.57	0.19	0.23	0.52
13.7	44.3	82.3	75.3	47.2	231.4	47.3	0.7	0.10	0.19	12.66	0.57	0.07	0.60	0.20	0.22	0.52
16.4	40.2	82.0	74.8	47.8	258.1	51.4	0.7	0.10	0.20	11.89	0.50	0.07	0.56	0.20	0.17	0.39
18.9	36.4	82.3	74.3	48.3	301.8	55.5	0.8	0.10	0.21	8.91	0.36	0.05	0.42	0.15	0.10	0.23
21.4	33.1	82.0	73.6	39.8	245.3	59.1	0.9	0.11	0.22	10.50	0.42	0.13	0.52	0.19	0.11	0.25
27.8	25.9	81.9	71.4	46.3	196.1	67.8	1.0	0.12	0.25	9.61	0.35	0.06	0.51	0.19	0.14	0.34
31.3	22.4	82.2	71.2	37.1	519.9	72.8	1.1	0.12	0.26	10.15	0.37	0.07	0.61	0.21	0.14	0.33
35.9	18.9	81.9	71.0	25.8	429.8	80.0	1.2	0.13	0.27	9.59	0.42	0.09	0.79	0.25	0.13	0.28
40.9	15.9	82.3	72.8	14.6	145.1	82.1	1.2	0.14	0.28	9.46	0.54	0.11	1.11	0.35	0.08	0.16
45.8	12.6	82.3	72.9	15.6	138.4	83.2	1.2	0.15	0.29	5.42	0.27	0.06	0.63	0.20	0.03	0.06
51.2	11.8	82.1	72.8	7.5	182.5	84.4	1.2	0.16	0.30	6.99	0.35	0.09	0.99	0.27	0.05	0.08
57.2	10.8	82.1	72.9	3.1	218.7	85.7	1.2	0.18	0.31	6.16	0.36	0.09	0.99	0.28	0.06	0.09
63.1	9.7	82.2	72.8	5.6	291.6	86.6	1.3	0.20	0.31	6.00	0.23	0.17	0.69	0.19	0.04	0.05
69.5	9.6	82.2	72.7	0.2	293.5	87.4	1.3	0.22	0.32	2.62	0.12	0.04	0.44	0.12	0.02	0.02
Total Condenstate										1.6	0.1	0.0	0.06	0.02	0.30	0.63

Laboratory Charge 2, 2x6 Douglas-fir, July 15, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC	g / kg_{ODwood} THC	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	d-limonene	p-cymene	4-terpineol	α-terpineol
2.7	57.7	81.7	75.1	3.1	2265.1	0.5	0.0	0.01	0.00	1.14	0.10	0.01	0.05	0.01	0.00	0.00
3.5	56.0	82.1	77.0	47.7	695.2	5.0	0.1	0.02	0.02	13.47	1.49	0.11	0.96	0.16	0.01	0.01
4.3	54.0	82.2	76.9	47.1	424.2	7.2	0.1	0.03	0.03	9.95	1.12	0.13	1.60	0.34	0.03	0.03
5.1	53.0	82.5	77.0	47.4	458.8	9.0	0.1	0.04	0.04	6.02	0.48	0.05	0.40	0.11	0.06	0.05
5.8	52.0	82.0	76.5	41.6	418.9	10.7	0.2	0.04	0.05	4.98	0.30	0.11	0.22	0.06	0.06	0.05
6.6	50.3	82.1	76.6	41.9	414.2	12.2	0.2	0.05	0.05	3.74	0.20	0.08	0.15	0.05	0.04	0.04
7.3	49.0	82.3	76.8	40.8	391.7	13.9	0.2	0.05	0.05	3.60	0.18	0.07	0.15	0.04	0.05	0.04
8.2	48.0	82.6	76.8	43.2	407.0	16.0	0.2	0.06	0.06	3.62	0.18	0.07	0.15	0.05	0.05	0.05
9.2	47.5	82.4	76.7	36.6	416.5	18.2	0.3	0.06	0.06	3.61	0.18	0.02	0.15	0.05	0.06	0.07
10.3	45.5	81.9	76.5	29.7	493.7	20.4	0.3	0.07	0.07	3.28	0.14	0.06	0.13	0.04	0.05	0.06
14.1	42.2	82.7	76.9	42.3	490.1	27.7	0.4	0.09	0.08	3.65	0.18	0.02	0.20	0.07	0.11	0.15
16.9	38.7	82.2	75.4	48.1	370.9	33.4	0.5	0.09	0.08	4.52	0.19	0.03	0.23	0.08	0.15	0.24
19.9	32.7	82.0	74.2	49.2	374.9	39.5	0.6	0.10	0.09	9.27	0.32	0.17	0.44	0.17	0.24	0.41
22.9	29.0	83.2	73.6	48.5	384.8	45.8	0.7	0.10	0.10	4.47	0.14	0.02	0.21	0.08	0.10	0.18
25.7	25.0	82.2	72.6	47.0	348.7	51.5	0.7	0.10	0.10	3.68	0.13	0.02	0.20	0.07	0.09	0.16
35.8	14.0	82.4	70.7	29.3	424.3	68.2	1.0	0.13	0.11	3.18	0.11	0.02	0.22	0.07	0.07	0.14
39.4	12.0	82.4	70.5	24.3	433.7	73.4	1.2	0.14	0.12	2.69	0.09	0.02	0.19	0.06	0.04	0.08
44.0	11.0	82.3	70.6	20.5	830.5	80.2	1.2	0.15	0.12	3.84	0.21	0.05	0.50	0.15	0.04	0.08
53.9	10.3	82.4	72.7	5.1	136.9	81.3	1.2	0.17	0.12	1.10	0.06	0.02	0.18	0.05	0.01	0.02
59.1	9.8	82.3	72.9	0.5	167.6	81.8	1.2	0.19	0.13	0.95	0.04	0.01	0.14	0.04	0.01	0.02
72.1	9.1	82.3	72.6	0.3	200.5	82.1	1.2	0.19	0.13	0.61	0.03	0.01	0.10	0.02	0.01	0.01
Total Condenstate										0.00	0.00	0.00	0.00	0.00	0.00	0.32

Laboratory Charge 3, 2x6 Douglas-fir, July 15, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min	Dry Basis THA Ppmv	g THC	g / kg_{ODwood} THC
		T_{db} °C	T_{wb} °C				
2	58.5	82.1	76.9	36.3	2118.1	5.1	0.1
4	54.4	82.2	76.2	44.2	679.4	19.3	0.3
5	52.6	82.2	76.1	44.3	534.1	22.5	0.3
6	50.8	82.1	75.8	44.0	430.1	25.0	0.4
7	49.1	82.5	75.7	44.1	360.7	27.1	0.4
9	45.7	82.4	75.3	44.4	287.9	30.4	0.4
11	42.4	82.0	74.7	44.2	241.7	33.2	0.5
15	36.5	82.4	60.0	79.0	102.8	37.7	0.5
20	30.6	82.3	70.7	24.4	142.2	42.0	0.6
25	24.6	82.3	70.5	40.4	156.7	46.0	0.7
30	20.3	82.0	70.5	24.9	166.5	49.1	0.7
35	16.9	82.7	69.4	24.3	147.8	51.5	0.7
40	14.6	82.1	70.6	13.3	240.9	53.2	0.8
45	13.2	82.4	71.8	3.6	295.1	54.7	0.8
50	12.5	82.3	72.8	3.6	373.9	55.5	0.8
55	11.9	82.2	72.5	3.5	364.9	56.4	0.8
60	11.3	82.1	72.0	3.8	337.0	57.2	0.8
62	11.0	82.4	72.1	3.7	335.9	57.6	0.8

Laboratory Charge 4, 2x6 Douglas-fir, July 18, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min	Dry Basis THA Ppmv	g THC	g / kg_{ODwood} THC
		T_{db} °C	T_{wb} °C				
2	49.9	81.8	71.9	3.6	3393.2	0.8	0.0
4	47.7	82.3	76.5	35.9	1572.1	20.6	0.3
5	46.2	82.1	76.7	32.8	1026.5	25.9	0.4
6	45.0	82.4	76.5	29.5	838.2	29.4	0.4
7	43.8	82.3	76.7	29.0	730.7	31.9	0.4
9	41.8	82.3	76.7	22.2	596.1	35.8	0.5
11	40.1	82.2	77.0	14.0	554.3	38.6	0.5
15	35.7	82.0	74.3	49.3	225.5	43.9	0.6
20	28.0	82.4	71.1	49.5	167.1	49.4	0.7
25	22.1	82.1	70.5	32.8	182.0	53.8	0.8
30	18.0	82.0	70.4	25.2	200.6	57.2	0.8
35	15.0	82.1	70.6	16.6	223.0	60.0	0.8
40	13.0	82.2	70.6	13.7	255.0	62.1	0.9
45	11.7	82.3	71.7	3.7	343.7	63.6	0.9
50	11.1	82.4	72.9	3.6	463.2	64.6	0.9
55	10.4	82.1	72.8	3.5	448.4	65.7	0.9
60	9.8	82.1	72.3	3.8	403.3	66.8	0.9
62	9.5	82.4	71.9	3.6	384.0	67.2	0.9

Laboratory Charge 5, 2x6 Douglas-fir, July 31, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC	g / kg_{ODwood} THC	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	d-limonene	p-cymene	4-terpineol	α-terpineol
2.9	64.1	77.4	58.3	4.1	719.7	0.3	0.00	0.02	0.00	1.01	0.11	0.02	0.02	0.01	0.00	0.00
3.6	64.1	81.5	72.0	4.1	2198.8	0.7	0.01	0.04	0.00	1.14	0.41	0.01	0.06	0.03	0.00	0.00
4.1	63.9	82.0	75.9	18.2	3471.4	2.2	0.03	0.06	0.01	1.26	0.85	0.03	0.15	0.07	0.01	0.00
4.7	63.4	82.2	76.9	28.0	2863.7	6.4	0.09	0.07	0.01	3.14	2.44	0.10	0.49	0.23	0.03	0.02
5.7	61.9	82.0	76.7	36.7	1186.7	14.2	0.20	0.10	0.04	10.05	1.08	0.06	0.27	0.15	0.05	0.03
6.8	60.4	82.1	76.8	35.7	827.5	18.3	0.26	0.12	0.05	7.23	0.67	0.09	0.18	0.10	0.04	0.03
7.3	59.7	82.1	76.6	29.6	714.5	19.9	0.29	0.13	0.06	6.60	0.50	0.03	0.14	0.08	0.04	0.03
8.3	58.4	82.6	76.7	31.9	614.6	22.4	0.32	0.15	0.07	5.53	0.34	0.02	0.10	0.06	0.04	0.03
9.7	56.5	82.1	76.7	30.7	536.1	25.6	0.37	0.17	0.08	5.13	0.35	0.02	0.11	0.07	0.05	0.04
10.5	55.5	82.3	76.6	26.8	495.7	27.1	0.39	0.18	0.09	4.83	0.30	0.02	0.11	0.07	0.04	0.04
11.2	54.5	82.3	76.5	34.2	455.5	28.5	0.41	0.18	0.10	5.05	0.30	0.02	0.11	0.07	0.04	0.04
12.8	51.9	82.3	75.5	45.4	329.6	31.5	0.45	0.20	0.11	7.38	0.24	0.02	0.10	0.07	0.05	0.04
14.1	49.6	82.1	74.8	51.0	284.2	33.7	0.48	0.21	0.12	6.94	0.44	0.08	0.21	0.14	0.11	0.10
15.9	46.3	82.8	73.5	60.5	229.6	36.7	0.53	0.21	0.12	6.11	0.36	0.07	0.18	0.12	0.10	0.10
17.8	42.5	82.3	72.3	66.1	210.7	39.8	0.57	0.22	0.13	6.95	0.37	0.08	0.20	0.13	0.11	0.11
22.0	34.6	82.4	69.8	71.6	170.4	46.0	0.66	0.24	0.16	20.74	0.29	0.06	0.19	0.12	0.07	0.08
27.6	25.5	82.1	66.4	66.0	140.0	53.2	0.76	0.26	0.18	9.34	0.42	0.09	0.25	0.18	0.09	0.09
30.9	21.6	82.0	65.4	53.2	143.3	56.4	0.81	0.27	0.19	10.98	0.59	0.07	0.49	0.29	0.09	0.11
38.8	16.0	82.4	65.7	27.1	172.7	61.9	0.89	0.29	0.21	6.04	0.37	0.09	0.32	0.18	0.04	0.04
44.1	13.7	82.7	65.5	20.9	184.2	64.4	0.92	0.31	0.21	2.37	0.40	0.05	0.42	0.23	0.04	0.04
50.3	11.8	82.2	65.5	15.2	211.1	66.7	1.03	0.34	0.22	5.85	0.51	0.06	0.61	0.28	0.05	0.04
72.8	8.0	82.2	65.5	6.4	250.3	72.1	1.06	0.35	0.22	0.74	0.02	0.00	0.02	0.01	0.00	0.00
Total Condenstate										0.00	0.00	0.00	0.00	0.00	0.47	1.25

Laboratory Charge 6, 2x6 Douglas-fir, August 3, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min	Dry Basis THA Ppmv	g THC	g / kg_{ODwood} THC
		T_{db} °C	T_{wb} °C				
2	63.0	82.4	71.8	79.9	756.7	6.8	0.1
4	57.9	82.2	72.6	81.0	373.8	17.7	0.3
5	55.8	82.2	73.5	52.0	429.7	20.9	0.3
6	53.9	82.5	73.9	53.6	387.6	23.6	0.3
7	52.1	82.1	73.8	51.0	350.0	25.9	0.4
9	48.9	82.2	73.8	48.8	307.5	29.6	0.4
11	45.8	82.2	73.8	44.3	299.8	32.8	0.5
15	39.1	82.2	71.8	58.1	199.4	38.9	0.6
20	30.6	82.2	69.1	65.5	167.3	45.6	0.7
25	23.3	82.3	65.8	55.1	146.0	51.5	0.7
30	18.9	82.3	65.4	30.0	168.0	55.7	0.8
35	16.2	82.4	65.6	19.6	187.7	58.6	0.8
40	14.3	82.1	65.5	17.8	190.6	60.8	0.9
45	12.8	82.3	65.5	16.9	211.1	62.7	0.9
50	11.6	82.1	65.3	10.7	226.6	64.3	0.9
55	10.7	82.3	65.5	13.9	247.0	65.7	0.9
60	9.9	82.2	65.6	5.4	250.0	66.9	1.0
71	8.7	82.2	65.5	5.3	283.1	68.7	1.0

Laboratory Charge 7, 2x6 Douglas-fir, August 6, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC	g / kg_{ODwood} THC	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	d-limonene	p-cymene	4-terpineol	α-terpineol
2.1	63.5	82.4	71.1	3.5	2433.7	0.7	0.0	0.01	0.00	0.80	0.38	0.01	0.07	0.02	0.01	0.00
2.6	63.0	82.1	74.2	37.8	2621.4	4.6	0.1	0.02	0.01	3.35	1.95	0.25	0.42	0.04	0.02	0.02
3.1	62.2	81.9	74.7	49.6	1413.2	9.9	0.2	0.04	0.03	18.00	2.37	0.09	0.55	0.07	0.05	0.04
3.6	60.9	82.4	73.9	79.3	689.8	13.9	0.2	0.06	0.05	17.19	1.64	0.21	0.46	0.09	0.07	0.05
4.1	59.8	82.3	73.7	71.6	558.3	16.4	0.3	0.07	0.06	13.57	0.94	0.15	0.28	0.08	0.06	0.05
4.6	58.7	82.2	73.7	65.2	478.7	18.4	0.3	0.08	0.08	10.20	0.62	0.10	0.19	0.40	0.30	0.30
5.2	57.6	82.3	73.8	58.9	419.4	20.2	0.3	0.08	0.09	9.23	0.55	0.09	0.17	0.07	0.06	0.04
5.7	56.5	82.3	73.8	60.7	363.0	21.8	0.3	0.09	0.10	8.87	0.48	0.07	0.15	0.07	0.06	0.05
8.0	52.5	82.2	73.9	52.0	310.0	26.5	0.4	0.10	0.11	6.44	2.41	0.10	0.69	0.35	0.25	0.26
16.0	39.2	82.1	71.3	64.7	159.1	37.9	0.6	0.14	0.15	28.26	7.26	0.30	2.09	1.04	0.74	0.77
24.2	26.0	83.8	66.8	70.3	117.6	46.4	0.7	0.15	0.17	14.15	1.02	0.16	0.49	0.09	0.09	0.00
35.7	16.7	82.3	65.6	25.3	150.8	53.5	0.8	0.20	0.21	40.03	2.71	0.44	1.32	0.79	0.25	0.24
48.0	12.4	82.5	65.8	15.3	179.2	57.9	0.9	0.20	0.21	0.32	0.51	0.05	0.53	0.04	0.03	0.00
57.4	10.5	82.5	65.5	6.7	209.0	60.3	0.9	0.22	0.22	2.55	0.62	0.06	0.63	0.22	0.05	0.04
66.7	9.1	82.0	65.5	4.6	230.5	62.1	1.0	0.23	0.22	0.10	0.22	0.02	0.31	0.02	0.02	0.00
72.0	8.6	82.1	65.6	3.8	236.1	62.8	1.0	0.23	0.22	0.45	0.06	0.01	0.08	0.02	0.01	0.00
Total Condenstate										0.01	0.01	0.01	0.03	0.00	2.51	6.39

Laboratory Charge 8, 2x6 Douglas-fir, August 18, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min	Dry Basis THA Ppmv	g THC	g / kg_{ODwood} THC
		T_{db} °F	T_{wb} °F				
2	63.3	82.2	68.2	3.7	1422.3	0.4	0.0
4	59.8	81.8	74.0	79.7	535.2	13.4	0.2
5	57.3	82.3	73.8	64.3	376.8	17.1	0.2
6	55.2	82.3	73.9	56.4	336.0	19.7	0.3
7	53.3	82.3	74.0	51.8	318.5	21.8	0.3
9	49.7	82.2	74.1	47.2	268.5	25.2	0.4
11	46.4	82.2	73.9	45.9	249.2	28.1	0.4
15	39.6	82.3	71.8	58.2	163.8	33.1	0.5
20	31.1	82.5	68.9	63.5	128.6	38.3	0.6
25	24.0	83.3	66.3	65.7	110.8	42.7	0.6
30	19.2	82.1	65.6	36.8	125.4	45.9	0.7
35	16.1	82.4	65.6	25.1	145.6	48.3	0.7
40	14.1	82.3	65.5	13.6	160.0	50.1	0.7
45	12.7	82.8	65.6	16.5	175.3	51.5	0.7
50	11.5	82.2	65.7	12.9	189.6	52.8	0.8
55	10.4	82.3	65.4	11.1	187.8	54.0	0.8
60	9.6	82.1	65.6	4.7	197.0	54.9	0.8
74	8.0	82.3	65.5	5.2	225.7	56.9	0.8

APPENDIX B Ponderosa pine data

Commercial Charge 1, Random Width Ponderosa Pine, September 9, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC	g / kg_{ODwood} THC	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	β-myrcene	p-cymene	4-terpineol
4.2	109.9	128.2	124.5	11.1	458.5	2712.0	0.0	14171.23	0.26	4.12	4.83	31.99	35.95	1.60	0.32
10.8	105.7	140.5	127.2	157.7	147.9	12146.5	0.2	18548.25	0.34	3.92	5.60	32.35	36.37	1.58	0.29
15.8	99.4	137.8	130.2	157.7	148.3	23932.7	0.4	27285.81	0.50	9.32	11.17	63.58	71.46	3.80	0.69
21.8	90.7	143.5	135.8	157.7	182.1	37180.0	0.7	35860.25	0.66	9.35	13.97	61.10	68.66	3.44	0.61
25.8	83.9	149.9	137.5	157.7	165.6	47088.6	0.9	46701.11	0.86	12.94	17.93	76.25	85.69	4.49	0.79
30.8	73.8	150.5	138.6	157.7	183.9	61456.8	1.1	62983.25	1.15	43.31	45.25	91.69	105.10	10.94	1.74
36.8	62.5	153.2	139.7	157.7	175.1	77331.2	1.4	75349.31	1.38	37.97	39.87	63.36	72.96	10.93	1.63
43.8	52.3	158.7	146.3	11.1	259.3	93652.8	1.7	81236.83	1.49	9.48	3.66	40.25	45.73	7.81	1.11
49.9	44.5	163.0	148.2	157.7	397.7	109772.3	2.0	87036.83	1.59	10.71	11.58	37.16	41.36	4.77	0.77
55.0	39.7	166.1	152.4	11.1	446.2	120442.7	2.2	89798.93	1.64	4.02	4.66	17.44	19.81	4.12	0.64
59.9	35.9	167.8	153.0	11.1	413.4	129547.2	2.4	91986.84	1.69	2.51	1.02	13.64	18.39	3.99	0.62
65.2	33.2	166.3	150.6	11.1	559.5	136294.7	2.5	92480.58	1.69	1.86	1.88	0.37	2.21	2.34	0.39
69.0	32.1	182.0	171.9	11.1	831.8	139542.7	2.6	93804.15	1.72	0.66	0.77	9.39	10.59	2.47	0.41
72.3	29.5	185.5	176.7	11.1	771.5	145261.1	2.7	95079.56	1.74	0.81	0.87	9.96	11.20	0.00	0.53
76.0	27.3	181.2	171.5	11.1	764.3	149280.5	2.7	95413.10	1.75	0.69	0.65	3.29	1.07	0.00	0.36
79.9	24.8	179.7	170.9	11.1	683.4	153527.5	2.8	100175.30	1.84	2.99	2.81	33.65	37.91	8.46	1.52
93.4	15.2	168.0	151.2	11.1	338.9	168712.2	3.1	101725.50	1.86	2.84	2.12	13.35	6.15	3.23	0.70
107.0	11.2	174.5	168.3	11.1	522.4	175472.5	3.2	111015.57	2.03	3.97	4.18	66.38	74.60	17.55	3.02
Total Condenstate										0.00	0.00	0.00	0.00	0.00	0.00

Commercial Charge 2, Random Width Ponderosa Pine, September 13, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC	g / kg_{ODwood} THC	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	β-myrcene	p-cymene	α-terpineol
4.8	141.7	131.2	129.2	11.1	20.6	623.8	0.0	6713.7	0.1	4.3	11.5	48.2	54.2	4.3	0.6
12.2	141.3	142.6	129.0	157.7	119.5	10381.7	0.2	3299.7	0.2	1.8	4.3	24.8	28.1	1.2	0.2
15.5	140.6	142.4	131.4	157.7	111.0	16501.9	0.3	704.3	0.2	0.4	0.9	5.3	6.0	0.3	0.0
20.1	139.1	146.7	130.6	157.7	93.9	24474.3	0.4	5120.5	0.3	2.9	6.7	38.9	43.3	1.8	0.3
26.8	135.5	161.5	139.6	157.7	190.6	38024.8	0.7	6387.6	0.4	3.8	7.9	48.6	54.6	2.0	0.4
31.7	131.8	164.4	139.8	157.7	176.7	53507.9	1.0	4991.5	0.5	3.0	6.2	38.0	42.7	1.6	0.3
35.9	127.8	168.6	138.5	157.7	176.5	65439.8	1.2	5096.5	0.6	3.3	6.8	38.5	43.1	1.6	0.3
39.8	123.3	164.9	133.4	157.7	150.2	75469.8	1.4	5406.2	0.7	3.6	7.2	40.6	45.6	1.8	0.4
43.6	118.5	168.8	128.8	157.7	120.3	83747.8	1.5	6170.0	0.8	4.5	9.4	45.6	51.2	2.1	0.4
48.3	111.8	166.0	151.7	11.1	613.6	93084.6	1.7	10792.9	1.0	11.0	24.6	72.9	82.2	6.5	1.1
54.0	103.2	181.1	118.6	157.7	122.7	107027.5	2.0	8782.3	1.2	11.4	22.4	56.4	64.6	5.4	1.0
57.9	96.9	167.9	152.1	11.1	694.9	112741.2	2.1	5577.8	1.3	7.8	15.4	34.5	39.6	4.3	0.8
59.9	93.6	166.7	152.5	11.1	725.5	115053.3	2.1	3555.9	1.3	5.4	10.9	20.8	24.0	3.6	0.6
64.3	86.4	164.9	149.6	11.1	495.3	119510.4	2.2	3214.1	1.4	3.3	6.3	21.6	24.3	3.0	0.5
68.5	79.3	171.5	156.0	11.1	545.7	123945.9	2.3	7767.1	1.6	7.7	12.7	55.2	59.9	6.1	1.0
72.2	72.8	181.6	171.0	11.1	749.2	127883.4	2.3	1992.5	1.6	4.7	6.4	12.5	9.0	3.3	0.7
77.1	64.1	178.9	168.7	11.1	513.1	133017.8	2.4	3375.5	1.7	8.1	9.4	17.8	17.8	7.2	1.6
82.6	53.9	177.3	166.5	11.1	362.5	137587.8	2.5	1587.9	1.7	3.8	4.4	8.4	8.4	3.4	0.8
85.5	48.1	177.2	166.1	11.1	425.4	139735.0	2.6	4812.5	1.8	4.8	5.0	37.7	36.2	3.6	1.0
89.0	41.5	178.6	167.6	11.1	362.8	142162.7	2.5	3989.1	1.8	4.8	4.6	27.0	32.0	3.8	0.9
92.9	33.5	125.2	97.5	157.7	30.1	144684.3	2.6	9011.1	1.9	7.8	8.0	67.6	76.0	4.6	1.3
103.2	19.5	178.1	172.7	11.1	422.6	149888.6	2.6	612.6	1.9	0.3	0.3	4.7	5.3	0.4	0.1
Total Condenstate										0.00	0.00	0.00	0.00	0.00	0.00

Laboratory Charge E1-20a, Random Width Ponderosa Pine, October 31, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min	Dry Basis THA Ppmv	g THC	g / kg_{ODwood} THC
		T_{db} °C	T_{wb} °C				
1	120.9	54.1	41.6	3.7	462.7	0.1	0.0
3	120.9	54.5	51.8	3.8	1153.3	0.9	0.0
5	120.5	57.1	54.6	80.5	662.5	4.9	0.1
7	118.7	57.2	54.2	88.7	158.6	9.8	0.1
9	116.6	59.1	55.0	127.7	133.1	13.3	0.2
13	109.4	62.6	55.7	186.8	88.3	21.3	0.3
15	104.7	64.6	60.0	186.7	96.5	25.4	0.3
18	96.8	65.5	60.0	186.9	94.4	31.8	0.4
20	91.7	65.6	57.4	186.7	85.7	35.8	0.5
25	79.9	71.3	59.3	192.1	95.6	45.9	0.6
30	66.5	76.4	60.4	192.1	109.7	57.4	0.8
35	54.6	77.0	59.7	146.8	113.1	68.7	0.9
40	45.8	76.8	63.8	100.6	211.4	80.7	1.1
45	37.6	77.8	62.1	100.0	186.5	92.2	1.2
50	30.4	82.2	65.5	67.1	307.8	104.2	1.4
55	24.7	82.2	65.5	47.7	337.2	115.6	1.6
60	20.5	82.1	65.6	41.2	341.4	124.6	1.7
65	17.3	82.3	65.2	30.1	352.0	131.6	1.8
70	13.4	88.4	59.6	76.1	191.1	138.9	1.9
77	8.9	87.7	60.2	36.0	257.1	148.2	2.0
82	7.0	87.9	60.1	22.5	328.9	153.0	2.1
88	5.5	87.7	60.0	13.4	379.9	157.6	2.1
92	4.9	87.9	59.8	12.7	422.1	160.0	2.2

Laboratory Charge 1-20b, Random Width Ponderosa Pine, October 14, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min	Dry Basis THA ppmv	g THC	g / kg_{ODwood} THC	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	β-myrcene	d-limonene	p-cymene
7.5	115.2	57.8	54.3	124.5	114.6	8.1	1.59	0.0	0.0	0.8	2.3	6.5	4.8	0.9	0.1
11.6	108.4	61.3	55.1	185.1	87.6	15.5	1.74	0.0	0.1	3.0	8.4	23.5	17.3	3.3	0.5
16.1	96.8	65.5	60.0	186.8	95.1	24.6	1.97	0.1	0.1	3.6	9.0	38.6	9.7	2.9	0.5
21.2	82.7	67.1	57.1	186.6	83.1	34.4	2.21	0.1	0.2	4.3	10.8	46.1	11.6	3.4	0.6
26.8	67.8	73.1	59.5	191.4	98.5	45.6	2.36	0.1	0.4	4.1	10.0	58.5	65.7	3.0	0.5
32.8	49.6	76.7	60.1	190.4	100.0	59.8	2.53	0.2	0.5	3.3	7.2	49.7	56.0	2.1	0.4
39.3	38.9	76.4	59.3	43.8	119.1	69.0	2.69	0.2	0.5	3.5	7.6	4.9	17.8	2.2	0.5
45.2	35.1	78.3	59.7	39.4	146.1	72.4	2.76	0.2	0.5	1.3	2.8	5.5	9.0	0.8	0.2
49.8	32.1	82.0	66.6	45.5	139.7	74.9	2.78	0.2	0.6	1.0	2.2	8.9	10.0	1.2	0.2
53.2	28.1	82.3	65.6	52.2	79.5	76.8	2.79	0.2	0.6	1.5	3.2	6.9	3.3	1.5	0.2
55.4	25.9	82.3	65.6	43.8	96.5	77.9	2.82	0.3	0.6	1.6	2.8	19.6	22.0	1.1	0.3
57.4	24.2	82.0	65.5	35.4	120.2	78.9	2.83	0.3	0.6	1.1	2.0	5.0	0.1	0.9	0.2
59.7	22.6	82.6	65.5	32.6	153.0	80.2	2.83	0.3	0.6	1.1	1.8	5.7	7.8	0.8	0.2
63.9	20.1	82.2	65.5	22.7	155.4	82.3	2.84	0.4	0.7	2.2	3.8	11.7	16.1	1.7	0.4
67.9	18.3	82.2	65.5	20.3	147.7	83.8	2.85	0.4	0.8	0.8	1.2	2.5	3.8	0.8	0.1
71.2	15.4	88.0	60.5	46.9	139.8	86.5	2.86	0.5	0.9	2.8	4.5	24.7	27.8	4.9	0.6
73.7	13.9	87.7	60.0	38.0	73.1	88.0	2.87	0.6	0.9	3.0	3.8	13.4	24.0	3.0	0.4
75.9	12.9	87.7	59.8	25.1	94.9	88.7	2.87	0.6	0.9	2.2	3.0	11.2	11.9	2.3	0.4
78.6	11.9	87.7	60.1	26.0	122.1	89.6	2.87	0.7	0.9	1.8	2.3	17.3	19.6	2.3	0.3
81.2	11.0	87.8	60.0	24.3	138.4	90.6	2.88	0.8	1.0	1.8	2.2	15.5	17.5	2.2	0.3
92.0	8.7	87.8	59.9	7.1	140.4	92.3	2.88	0.8	1.0						
Total Condenstate										0.02	0.03	0.25	0.00	0.00	0.00

Laboratory Charge E21-40a, Random Width Ponderosa Pine, November 4, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min	Dry Basis THA Ppmv	g THC	g / kg_{ODwood} THC
		T_{db} °C	T_{wb} °C				
1	101.0	53.9	43.8	3.7	437.5	0.1	0.0
3	101.0	55.1	52.4	3.8	892.5	0.8	0.0
5	100.4	57.3	54.7	75.0	368.6	4.7	0.1
7	98.7	57.3	54.6	87.1	164.1	8.3	0.1
9	96.2	59.0	54.1	140.9	95.5	11.7	0.2
13	89.5	62.6	55.1	184.1	97.2	19.3	0.3
15	84.9	64.5	60.0	184.0	106.3	23.7	0.3
18	77.1	65.8	60.0	183.9	105.5	30.7	0.4
20	71.9	65.6	55.9	183.9	94.8	35.2	0.5
25	61.0	71.3	57.3	190.7	83.2	45.0	0.7
30	50.0	78.0	59.9	150.1	117.5	54.6	0.8
35	39.8	76.8	59.8	128.8	138.0	66.1	1.0
40	31.9	76.6	59.8	107.1	159.5	76.6	1.1
45	25.8	78.0	61.0	67.0	197.5	85.5	1.2
50	20.8	82.3	64.5	43.9	309.1	94.0	1.4
55	16.9	82.2	65.6	30.6	373.6	102.1	1.5
60	14.1	82.1	65.5	24.3	405.5	108.8	1.6
65	12.1	82.1	65.3	17.9	436.3	114.0	1.7
70	9.4	88.1	59.9	53.2	207.8	119.9	1.7
77	6.4	87.7	60.0	19.8	279.6	126.5	1.8
82	5.0	87.9	60.0	19.2	306.5	129.9	1.9
88	4.0	87.7	59.9	9.2	371.9	133.1	1.9
92	3.5	87.7	60.0	9.5	416.1	134.8	1.9

Laboratory Charge 21-40b, Random Width Ponderosa Pine, October 14, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min*	Dry Basis THA ppmv*	g THC*	g / kg_{ODwood} THC*	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	β-myrcene	d-limonene	p-cymene	α-terpineol
6.1	99.5	56.9	54.9	25.0	681.2	4.0	0.1	0.05	0.01	0.19	0.53	2.15	2.41	0.08	0.02	0.01
7.0	99.0	57.4	54.5	61.4	238.9	5.8	0.1	0.09	0.04	0.65	1.81	16.51	18.57	0.72	0.15	0.02
10.5	95.3	60.2	54.4	159.1	93.9	13.5	0.2	0.15	0.19	3.70	14.50	56.80	63.84	2.61	0.47	0.46
17.0	83.8	65.6	60.0	177.0	91.6	26.3	0.4	0.20	0.37	4.88	18.41	73.29	82.53	2.71	0.54	0.47
25.0	68.8	72.2	57.6	185.9	110.1	43.1	0.6	0.24	0.55	11.32	41.34	79.45	34.63	8.28	1.05	0.30
27.9	58.6	74.8	59.8	130.7	106.0	51.5	0.7	0.29	0.73	11.22	41.98	82.78	35.57	8.30	1.04	0.31
34.3	45.0	76.4	58.5	142.1	114.8	65.5	0.9	0.33	0.84	4.20	13.91	44.59	50.11	2.29	0.44	0.18
40.8	25.0	76.9	51.6	53.9	71.2	79.6	1.2	0.35	0.94	11.23	38.62	28.15	6.21	8.34	1.21	0.19
46.7	19.7	80.2	62.9	50.0	113.9	83.3	1.2	0.41	1.02	3.71	11.30	33.42	36.82	1.90	0.40	0.04
49.0	17.9	82.2	65.4	49.9	24.8	84.8	1.2	0.45	1.07	4.13	12.37	18.04	8.46	2.89	0.45	0.03
52.5	15.4	82.0	65.5	37.1	58.7	85.6	1.2	0.50	1.12	2.39	6.83	18.77	19.64	1.47	0.30	0.03
59.9	12.0	82.1	64.4	26.2	103.8	88.3	1.3	0.55	1.15	1.57	4.31	11.83	12.37	0.92	0.20	0.02
61.1	11.5	82.1	63.7	26.0	86.2	88.6	1.3	0.60	1.18	1.73	4.22	7.63	8.57	2.67	0.42	0.03
64.7	10.2	82.2	62.3	26.0	36.9	89.3	1.3	0.64	1.20	1.73	4.15	7.59	8.53	2.66	0.41	0.03
67.9	9.8	82.3	65.6	5.6	141.4	89.8	1.3	0.65	1.20	0.44	0.81	0.65	0.08	0.42	0.09	0.01
91.787	4.4	87.6	59.9	3.5	98.5	94.1	1.4	0.66	1.21	0.98	1.45	0.80	2.26	0.81	0.16	0.03
Total Condenstate										0.1948	0.2905	1.88083	2.113225	0.10253	0.042151	4.202526

* Data may not be accurate because of limited venting capacity, the schedule required more venting than the flow meters could supply.

Laboratory Charge E41-60a, Random Width Ponderosa Pine, October 18, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min	Dry Basis THA Ppmv	g THC	g / kg_{ODwood} THC
		T_{db} °C	T_{wb} °C				
1	133.9	55.0	39.3	3.6	470.8	0.1	0.0
3	133.9	54.3	51.1	3.8	1520.5	1.2	0.0
5	133.7	57.1	54.6	22.4	1602.0	3.4	0.0
7	131.6	57.1	54.2	94.0	192.9	12.1	0.2
9	129.1	58.8	54.1	138.4	115.4	16.2	0.2
13	121.2	62.6	55.5	188.2	84.7	24.7	0.4
15	116.1	64.3	60.0	188.1	111.9	29.2	0.4
18	107.4	65.7	60.0	188.1	118.8	35.9	0.5
20	101.7	65.6	56.9	187.8	86.3	40.2	0.6
25	89.0	72.0	59.2	190.7	91.3	50.3	0.7
30	74.6	76.7	60.8	190.5	106.2	61.4	0.9
35	61.6	76.5	60.1	161.8	116.0	72.3	1.0
40	50.8	76.8	59.6	135.8	115.6	82.2	1.2
45	41.6	77.9	57.7	136.1	102.6	90.8	1.3
50	33.7	82.2	65.4	76.7	282.2	100.7	1.4
55	26.8	82.3	65.5	56.3	307.0	112.3	1.6
60	21.8	82.3	65.5	39.6	339.5	121.5	1.7
65	18.2	82.0	65.6	29.0	374.6	128.8	1.8
70	14.2	87.8	60.0	66.2	181.6	135.9	1.9
77	9.6	88.0	60.0	36.7	228.2	144.0	2.1
82	7.4	87.8	59.9	20.1	283.2	148.1	2.1
88	5.8	87.7	60.0	10.8	317.4	151.9	2.2
92	5.2	87.7	60.0	14.1	346.2	153.8	2.2

Laboratory Charge 41-60b, Random Width Ponderosa Pine, October 4, 1997										mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}	mg / kg_{ODwood}
Mid Interval Time	MC %	Temps T_{db} °C	Temps T_{wb} °C	Venting Rate l/min*	Dry Basis THA ppmv*	g THC*	g / kg_{ODwood} THC*	g Monoterpene	g / kg_{ODwood} Monoterpene	α-pinene	β-pinene	Δ-3-carene	β-myrcene	d-limonene	p-cymene	α-terpineol
6.9	129.6	57.3	55.0	52.0	747.8	10.4	0.1	0.04	0.01	0.25	1.71	4.20	1.89	0.15	0.05	0.01
10.2	126.1	60.0	55.7	158.2	138.3	19.9	0.3	0.06	0.06	2.54	13.44	26.07	11.54	1.20	0.29	0.12
15.0	117.9	64.5	60.0	175.3	116.8	31.2	0.4	0.09	0.15	4.20	22.23	43.10	19.08	1.98	0.48	0.20
20.9	106.6	66.4	65.8	95.3	111.0	44.3	0.6	0.09	0.18	5.23	3.73	8.78	7.28	2.10	0.55	0.21
22.2	105.4	68.3	58.5	100.2	88.4	45.6	0.7	0.12	0.25	11.96	8.53	20.09	16.66	4.80	1.26	0.49
27.8	95.3	74.9	63.5	158.6	128.8	53.1	0.8	0.13	0.27	6.34	6.81	5.66	2.62	2.16	0.68	0.14
32.8	79.6	76.6	63.9	183.0	134.5	66.8	1.0	0.14	0.31	10.25	10.99	9.13	4.22	3.49	1.10	0.23
38.3	58.0	77.3	63.8	130.7	151.1	81.4	1.2	0.15	0.35	10.00	8.28	13.05	5.12	3.01	1.08	0.14
44.1	42.5	76.2	47.6	3.8	105.9	96.2	1.4	0.16	0.38	6.37	15.00	3.60	1.54	1.86	0.74	0.06
48.9	35.0	81.9	67.0	102.4	232.3	107.3	1.5	0.17	0.42	4.90	14.81	10.46	7.48	1.50	0.66	0.06
52.6	28.4	82.2	65.8	98.8	211.1	117.4	1.7	0.24	0.58	19.58	43.02	28.25	53.81	6.05	3.74	0.30
68.1	14.4	85.4	64.3	44.4	276.6	148.0	2.1	0.25	0.74	3.21	7.06	4.63	8.83	0.99	0.61	0.05
72.1	10.8	87.9	60.0	79.6	169.8	155.3	2.2	0.26	0.80	4.27	8.82	5.48	1.21	1.32	0.95	0.08
76.1	8.5	87.9	60.4	62.0	232.5	160.9	2.3	0.28	0.81	2.78	5.27	3.84	5.92	0.83	0.58	0.04
80.3	6.9	87.5	59.9	5.7	236.3	165.5	2.4	0.34	0.84	3.07	5.69	19.42	21.82	1.13	0.60	0.24
92.0	4.3	88.1	60.1	15.2	333.1	174.7	2.5	0.34	0.89	0.15	0.28	0.94	1.06	0.05	0.03	0.01
Total Condenstate										0.16	0.12	1.47	1.94	0.21	0.08	8.47

* Data may not be accurate because of limited venting capacity, the schedule required more venting than the flow meters could supply.

Laboratory Charge E61-80a, Random Width Ponderosa Pine, October 26, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min	Dry Basis THA Ppmv	g THC	g / kg_{ODwood} THC
		T_{db} °C	T_{wb} °C				
1	147.3	54.5	41.4	3.5	546.4	0.1	0.0
3	147.2	54.6	51.8	3.4	1397.2	1.1	0.0
5	147.0	57.0	54.8	22.3	1296.9	3.8	0.1
7	144.6	57.0	53.9	91.4	144.7	10.7	0.2
9	141.5	59.1	54.8	143.0	120.4	14.6	0.2
13	132.9	62.8	57.1	169.4	116.9	23.5	0.4
15	127.8	64.3	60.0	169.4	123.8	28.4	0.4
18	119.3	65.2	60.0	190.0	98.6	35.7	0.6
20	113.2	66.1	57.7	189.9	88.0	39.9	0.6
25	98.8	71.1	59.9	190.3	94.5	50.0	0.8
30	82.4	77.4	61.7	189.8	108.5	61.3	1.0
35	66.8	77.0	59.8	177.2	101.5	72.8	1.1
40	54.7	76.5	58.8	151.4	101.2	82.6	1.3
45	44.0	77.5	60.9	120.8	147.8	92.6	1.4
50	34.1	82.4	65.6	88.1	243.8	104.3	1.6
55	26.0	82.3	65.5	60.4	287.9	115.7	1.8
60	20.5	82.1	64.4	47.7	298.0	124.9	1.9
65	16.1	82.3	60.6	47.6	235.9	132.5	2.1
70	12.7	87.7	59.7	56.4	208.6	139.1	2.2
77	8.5	87.9	59.8	27.4	272.7	147.3	2.3
82	6.6	87.7	60.0	20.0	308.0	151.4	2.4
88	5.1	87.8	60.0	11.3	344.9	155.2	2.4
92	4.4	87.6	60.0	13.8	378.1	157.2	2.4

Laboratory Charge E61-80b, Random Width Ponderosa Pine, September 29, 1997							
Mid Interval Time	MC %	Temps		Venting Rate l/min*	Dry Basis THA ppmv*	g THC*	g / kg_{ODwood} THC*
		T_{db} °C	T_{wb} °C				
1	151.8	54.9	38.0	3.7	383.1	0.1	0.0
3	150.3	54.5	51.2	3.7	1825.9	1.3	0.0
5	148.8	55.6	53.9	3.7	1895.9	3.2	0.0
7	147.3	57.3	55.4	0.4	738.4	4.9	0.1
9	144.6	59.0	56.0	46.7	219.9	8.0	0.1
13	139.3	63.1	56.0	56.0	235.1	12.2	0.2
15	136.3	64.4	60.0	46.2	170.7	14.4	0.2
18	131.3	65.5	60.0	57.3	148.9	17.3	0.3
20	127.9	65.6	61.4	57.3	231.6	19.8	0.3
25	118.6	71.0	65.7	47.1	265.6	27.5	0.4
30	107.4	76.5	69.8	59.0	301.6	36.3	0.6
35	95.2	76.7	69.5	48.4	267.3	45.2	0.7
40	83.1	76.9	69.3	48.7	231.8	53.0	0.8
45	71.3	77.7	68.8	58.2	210.8	59.9	0.9
50	58.7	82.2	71.6	48.2	244.5	67.1	1.0
55	45.7	82.1	70.7	48.3	216.4	74.4	1.2
60	33.4	82.5	69.0	57.9	191.2	80.8	1.3
65	22.3	82.3	65.9	55.7	168.7	86.5	1.4
70	12.2	88.0	64.3	58.0	189.3	92.5	1.4
77	5.1	88.3	61.2	57.7	164.9	96.9	1.5
82	5.1	88.3	61.2	57.7	164.9	96.9	1.5
88	5.1	88.3	61.2	57.7	164.9	96.9	1.5
92	5.1	88.3	61.2	57.7	164.9	96.9	1.5

* Data may not be accurate because of limited venting capacity, the schedule required more venting than the flow meters could supply.